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BIOLOGY-INSPIRED AUTONOMOUS CONTROL

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14. ABSTRACT

The goal of this project was to motivate development of control concepts for autonomous weapons that overcome limitations of conventional approaches by applying principles derived from studying the biology of flying organisms. The research was focused on understanding the mechanisms of biological flight through collaboration with various experimental biology academic research laboratories around the world. The research focus addressed two broad, complementary research areas: *autonomous systems concepts* inspired by the behavior and neurobiology associated with spatial orientation, target pursuit and navigation in insects, birds and bats and *agile autonomous flight* inspired by the biomechanics, aerodynamics, sensing and neurobiology of flapping flight. Technical papers produced during this project, included in the appendices, highlight promising new research directions associated with development of autonomous aerial systems for weapon and other Air Force applications.

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BIOLOGY-INSPIRED AUTONOMOUS CONTROL

Final Report

June 2011

Preface

This report documents a body of basic research conducted by the Flight Vehicles Integration Branch, Assessment and Demonstrations Division of the Air Force Research Laboratory Munitions Directorate, Eglin Air Force Base, Florida. The research was documented in technical journal articles and conference proceedings included in this report.

Acknowledgments

Summary

The goal of this project was to motivate development of control concepts for autonomous weapons that overcome limitations of conventional approaches by applying principles derived from studying the biology of flying organisms. The research was focused on understanding the mechanisms of biological flight through collaboration with various experimental biology academic research laboratories around the world. The research focus addressed two broad, complementary research areas: *autonomous systems concepts* inspired by the behavior and neurobiology associated with spatial orientation, target pursuit and navigation in insects, birds and bats and *agile autonomous flight* inspired by the biomechanics, aerodynamics, sensing and neurobiology of flapping flight. Technical papers produced during this project, included in the appendices, highlight promising new research directions associated with development of autonomous aerial systems for weapon and other Air Force applications.

Autonomous Systems Concepts
The *2010 Air Force Chief Scientist Report on Technology Horizons*[1] highlights "trusted, adaptive, flexibly-autonomous systems" as "powerful force multipliers" for the Air Force of the future. Obviously, the context for this strategic technology vision involves the development of human-centric air power capabilities for the delivery of desired effects in the conduct of US foreign policy. But the report further envisions "operations at timescales far faster than possible with human-in-the-loop control" that are enabled by the incredible advances in computer-based technologies for automation of the past few decades. Over the past century, machines capable of faster-than-human response times have become pervasive, though their use has, until quite recently, been limited to augmentation of human function. For example, while tactical missiles have order-of-magnitude faster response times than human piloted aircraft, they have been employed as smart bullets rather than autonomous agents. Thus a tactical missile weapon system employed against a target threat is currently governed by human sensory processing, human decision making, and human response associated with the human-perceived threat. *Technology Horizons* motivates serious consideration of significantly expanded capabilities for autonomy well beyond those of current Air Force systems.

The online Oxford Dictionary defines *autonomous* as "acting independently or having the freedom to do so".[2] This definition characterizes the most obvious feature of biological flight: flying organisms exploit real-world aerial environments without aid or external control from other entities. It also characterizes human piloted aircraft and other such systems in which human sensing-processing-response capabilities, increasingly augmented with electronic devices, provide the independence of action we associate with "autonomous". However, it has only limited applicability to current unmanned aerial vehicles. Even though some unmanned aerial vehicles demonstrate impressive feats of independent flight,[3] none built to date exhibit the astonishing agile autonomous flight capabilities of insects, birds and bats.

It is clear that a move from man-in-the-loop systems to truly autonomous systems is presents significant engineering challenges. Man-in-the-loop systems are designed to produce an overall system response that is compatible with human sensing/decision/response capabilities. To accomplish this, while it is usual for such systems to employ faster-than-human-response internal processes, such processes are designed so that they are not destabilized by the human input and do not overload the human operator. Moving the human input to a higher system level (e.g., from active moment-to-moment decision making to occasional monitoring) necessitates substantial redesign and analysis to verify the performance and stability of the overall system. And, as *Technology Horizons* suggests, there are also challenges associated with development of verification and validation (V&V) methods and tools that will allow highly autonomous systems to be safely employed in close proximity to humans.[1]

While engineered aerial autonomous systems are just beginning to be developed, non-human biological autonomous systems are ubiquitous: insects, birds and bats. Studies of animal flight may provide insights into fundamental principles by which flying organisms achieve their impressive capabilities for agile autonomous flight. It is reasonable to expect that some of these principles, though perhaps not all, will be useful for the development of similar capabilities in engineered aerial autonomous systems. During the course of this project, researchers investigated autonomous systems concepts inspired by the behavior and neurobiology associated with spatial orientation, target pursuit and navigation in insects, birds and bats. Appendix A contains two technical papers that contrast notions of autonomous systems associated with biological and engineered aerial systems. In the first paper, Evers[4] argues that two issues dominate the difficulty of achieving engineered autonomous flight comparable to that of living organisms: *it is nearly impossible to correlate biological processes with engineering design principles; biological*

systems possess sensing-computation-actuation response architectures and processes that appear to differ from those of engineered systems in fundamental ways, those differences are poorly understood, and their importance little appreciated. These issues present opportunities for the biological and engineering sciences to expand the ranges of their respective research domains through collaborative efforts to understand biological flight and the mechanisms that enable it. Unfortunately, innate differences in approach, methodology, theory and even attitude toward scientific inquiry tend to inhibit the effective integration of engineering and biological sciences in developing an understanding of mechanisms enabling animal flight and developing applications based on that understanding.

In the second paper, Evers[5] addresses some of the technical challenges associated with development of bird or insect size micro autonomous aerial systems. The paper presents arguments from the perspective that systems envisioned as employing agile micro autonomous aerial vehicles represent complex, highly nonlinear multi-scale (both temporal and spatial) dynamical systems. After a brief description of some issues of scale for such systems and current research investigating those issues, the paper focuses on a discussion of characteristics of autonomy associated with living aerial organisms. Since agile micro autonomous aerial systems currently exist only in nature (i.e., insects, birds, bats), the paper considers autonomy from a biological perspective then extrapolates distinctly biological notions of autonomous behavior to eventual application in manmade systems. In particular, the paper suggests that response variability and flexibility may be intrinsic attributes of biological autonomous flight. It introduces a conjecture that this flexibility and variability in response is motivated by the necessity of responding appropriately to essentially unpredictable disturbances. By extension, the development of highly autonomous engineered aerial systems may require those systems to possess levels of response variation and flexibility that are not currently characteristic of, and perhaps will not be tolerated in, manmade critical systems. Although this paper does not directly address questions of ethics associated with the deployment of critical autonomous systems (whether intentionally lethal or not), it attempts to provide some insight into how those important questions may naturally emerge when any degree of robustness is imposed as a design criterion for such systems.

Agile Autonomous Flight

Key functional requirements for a vehicle, manmade or biological, to achieve autonomous flight are easy to enumerate: it must have capabilities to sense its surroundings and to aerially maneuver in a stable way among objects or other vehicles in its surrounding. Of course, these imply that the vehicle can sense and respond to its own motion, whether that motion is produced through its response actions or from external disturbances. Further, the response of such a vehicle is dominated by decision processing that integrates external sensory information with propriosensory information so that the response appears to an independent observer to be stochastic. This does not mean that the response is random but that it is predictable to an observer only in a statistical sense, given the observer's limited access to the complete spectrum of sensory information and decision processing producing the vehicle's response.[5]

A motivation for developing agile autonomous flight comparable to that of flying animals may be most easily envisioned by considering micro aerial systems operating in confined, obstacle-cluttered airspace. As Ol, et al.,[6] discuss, the desire to operate such systems in complex environments present unique engineering design challenges associated with the low-inertias, low wing loading, low Reynolds number aerodynamics, and structural flexibility associated with such vehicles. Since a detailed understanding of the physics of animal maneuvering flight is yet to be developed, existing micro aerial system designs tend to be *ad hoc* and based on trial-and-error experience rather than fundamental engineering principles. The paper describes several

investigations into low Reynolds number aerodynamics, flexible wing structures, autonomous flight control and fundamental studies of animal flight that are beginning to establish a physics-based foundation for the development of small agile autonomous aerial vehicles.

Achieving agile autonomous flight in manmade aerial systems based on studies of biological flying organisms requires integration of on-board sensing of the vehicle's own position/motion with on-board sensing of the external surroundings. Unlike manmade aerial vehicles which typically use inertial rate gyro and accelerometer feedback for flight stabilization, flying organisms co-opt other sensory modalities for flight control. Motivated by the observation that wing load sensing, through various sensory mechanisms, seems to be characteristic of the neuromorphologies of all flying organisms, Thompson, et al.,[7] investigated the potential use of load sensors on small air vehicle aerodynamic surfaces to enhance body platform stability. Two complementary techniques were explored: one using body torque error to control actuator position and the other using body force sensing to compensate for high optical feedback latency. The benefits of responding reflexively to forces on the aerodynamic surfaces identified include low latency disturbance response, a reference frame inherently consistent with the control actuation, and alleviation of the necessity for control based explicitly on aerodynamic characterization. The authors documented use of 6 degree-of-freedom simulation to demonstrate the robustness derived from load sensing in a turbulent flow field with high levels of plant uncertainty and optical feedback latency. The results of this paper suggest that direct sensing of forces acting on the body can significantly enhance the robustness and performance of an attitude control system. The authors suggested that this provides insight into how natural systems can fly with high levels of damage, coarse sensors, and large sensorimotor information processing latencies.

Impressive though animal aerobatics may appear in casual observation, detailed analysis of animal flight is a significant challenge, as evidenced by the work of Chakravarthy, et al.[8] The authors describe the collection, post-processing and subsequent evaluation of flight data of maneuvering butterflies, in various free flight scenarios in a quasi-natural environment. A two-camera stereovision tracking system was used to obtain the flight video image sequences. Post processing imagery was used to determine estimates of the motion of different body parts of the insect, including the relative motion of abdomen and the wings. These estimates were subsequently analyzed with a view to establishing the manner in which the insect coordinates its abdominal motion with the motion of its wings during a flight maneuver. Furthermore, the manner in which this coordination changes through different flight phases was studied with the goal of cataloging classes of maneuvers and their associated kinematics.

Commensurate with the challenges of kinematics reconstruction, modeling of the flight dynamics of flying organisms is a work-in-progress. Chakravarthy, et al.,[9] explored the issues of control of aeroelastic wing micro autonomous aerial systems. The authors proposed that controllers designed using methods applicable to larger aircraft are unlikely to realize the agile flight potential of flexible wing micro autonomous aerial systems airframes. Departing from conventional air vehicle rigid body dynamics models, the authors proposed a configuration of two Euler-Bernoulli beams connected to a rigid mass to represent a conceptual model of an aeroelastic wing micro autonomous aerial system. Continuous Sensitivity Equation Methods were employed to examine the sensitivity of the controlled state with respect to variation of the $H_{Infinity}$ control parameter, with the primary goal being to gain insight into the flexible dynamics of the system in order to exploit the utility of wing flexibility for control purposes. The paper further examined functional gains in order to determine optimal sensor placement while taking advantage of the flexibility of the micro autonomous aerial systems model.

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Appendix A

Biological Inspiration for Agile Autonomous Air Vehicles

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ABSTRACT

The ease with which flying insects, birds and bats negotiate confined, obstacle-cluttered airspace has long inspired us with visions of human-designed aerial machines with similar performance. Flying animals exhibit capabilities for aerial acrobatics, insensitivity to wind gusts, avoiding collision with or intercepting fixed and moving objects, landing and take off from small perches, and numerous other feats of flight agility that are beyond those of human-engineered vehicles. Although we are naturally tempted to look to biological organisms for inspiration or as design templates, the performance of the resulting bio-inspired or biomimetic engineered devices rarely approaches that of the living organisms. Among several possible reasons for this, two important issues motivate and provide a focus for this paper: it is nearly impossible to correlate biological processes with engineering design principles; biological systems possess sensing-computation-actuation response architectures and processes that appear to differ from those of engineered systems in fundamental ways, those differences are poorly understood and their importance little appreciated. These issues provide rich opportunities for research to produce genuine advancements in our understanding of biological and artificial autonomy. The research will necessarily involve biologists, engineers, and mathematicians. As with any research endeavor involving multiple mature disciplines, long term research collaborations are necessary for establishing the foundation of fundamentally new science. Unfortunately, without an objective understanding of these two issues and their implications for guiding autonomous air vehicle research and development, the real promise for biology-inspired or biomimetic concepts to achieve breakthroughs in vehicle capabilities may remain an elusive dream.

1.0   INTRODUCTION

Today's tactical munitions and unmanned air vehicles (UAVs) rely on guidance systems that are based upon relatively few high-quality sensors, centralized digital data processing, model-based algorithm designs, high-speed digital microprocessors, and relatively tight tolerances on sensor, processing, and actuator subsystems. Development of future low cost munition systems, small UAVs (SUAVs) and micro air vehicles (MAVs) for more challenging engagement environments is limited by the capabilities of current guidance system technologies. To appreciate this, consider a not unreasonable extension of a wide area autonomous search (WAAS) munition operational scenario. Here small autonomous MAVs have the mission, individually and in cooperation with similar vehicles, to search for, acquire, identify, track, and intercept deceptive targets in a cluttered imperfectly known environment. The particular scenario could be a group of tactical munitions on a mission to detect and destroy missile launchers that are operating in the back alleys of an urban areas or search and rescue MAVs combing a tree covered canyon for a downed aircrew. To accomplish these kinds of missions, MAVs require some combination of on-board sensors and limited communication to seek out and

intercept their actual targets in information rich environments that include other MAVs, SUAVs, stationary and moving objects to be avoided, and potential targets. Given the high uncertainty associated with these kinds of scenarios, significant levels of aerodynamic agility and operational autonomy will be required. Current guidance systems technologies do not, in general, yield the kinds of performance and uncertainty robustness when applied to SUAV or MAV scales.

The notion of agile autonomy, in the sense of robust negotiation of confined airspace such as forest edges, canyons, and urban areas, provides a prime motivation for looking to biology for inspiration for MAV designs. A person who disturbs a nest of ground wasps experiences, perhaps painfully, the incredible aerial pursuit capabilities of these small animals. It is easy to imagine that swarms of MAVs could similarly prosecute fleeing terrorist vehicles in urban canyons while ignoring noncombatant vehicles and individuals. Unfortunately there are few analogues of the supervised autonomy envisioned for human war machine systems to be found in nature. Even within the most tightly social animal groups, the social ants, bees, and termites, normal large variations in individual response exist that would be unacceptable in human weapon systems. Biologists characterize these individual response variations stochastically and design behavior experiments using sample sizes as large as practical in order to detect trends and, hopefully, construct cause and effect hypotheses that explain the behavior. The behavioral variation that is inherent and essential for a robust, evolvable biological system may be a critical flaw in a human designed system. A challenge, then, is not just to identify and characterize the mechanisms underlying animal autonomous response, a difficult enough task, but to develop a framework of system autonomy from that understanding that exploits tolerable response variation while providing reasonable guarantees that critical pathological responses will not emerge.

Engineered guidance and control systems built from integrated functional components are probably poor analogues for biological sensorimotor systems. While an inertial measurement unit for an air vehicle is a device that may be calibrated and bench-tested during integration with the rest of the guidance system, the functional equivalent in dipterous flies probably involves, at a minimum, modified wing structures (halteres) and their associated strain receptors, strain receptors at the base of the wings themselves, head-neck postural receptors, and specialized neural pathways associated with the compound eye and ocellus (simple eye) vision systems. That is, the insect's "inertial sensor" consists of distributed receptor structures and organs functionally integrated with the wing control muscles through decentralized processing channels. This kind of distributed sensorimotor architecture seems to be pervasive in biology. In fact, an argument can be made that, as with body dynamics sensing in the fly, most biological sensing involves structures and processes that only function as sensors in the context of the closed-loop system responses to which they contribute. This implies that system engineering from components which have specialized and compartmented functions is a poor paradigm for understanding the design architecture of flying animals. The challenge is for engineers and biologists to collaborate on development of sensorimotor architecture concepts for context appropriate response that will provide insight into the biology and serve as guides for design of new manmade systems.

2.0   WHY AGILE AUTONOMY?

A quick perusal of headlines in any major newspaper presents reminders that with the undeniable capabilities of today's military systems, conflict in mountainous, forested terrain and urban canyons remains a challenge. Threats capable of blending with non-combatant populace may be nearly impossible to detect, track, and prosecute with conventional assets in these kinds of environments. Given that military conflict of this sort may remain an avenue by which nations attempt to resolve ideological and political differences for the foreseeable future, we must explore new capabilities to meet the associated technology challenges.

Although UAVs have established an impressive performance record during the course of the current Middle

Eastern conflict, operation of large UAVs in urban canyons is not practical. Existing SUAVs and MAVs, although demonstrating considerable utility as information-surveillance-reconnaissance (ISR) assets, have only limited capabilities for operation in the confined, obstacle cluttered environs of city streets. Issues such as communication latency and drop-out; the ability to operate in close proximity to terrain, structures, and other vehicles; the ability to land and perch on stationary or moving objects; and sufficient autonomy for reasonable operator workload point to significant limitations in current technologies. Given the dynamic nature of urban combat, operation in those scenarios is dominated by uncertainties. Vehicles move, buildings are damaged or destroyed, barriers are constructed or removed, people congregate or disperse, all on time-scales that quickly render outdate the most detailed "current" information. Air vehicles capable of covert operation in urban canyons will have to contend with stationary and moving obstacles, dynamically variable winds and gusts with velocities close to those of the vehicles, severely limited line-of-sight sensor and communication paths, broadly variable illumination and spatially complex backgrounds and hostile action. These challenges drive the need for high levels of airframe agility and significant capabilities for autonomous flight using on-board sensors. (Some of these ideas receive expanded discussion in Kloeppel, 2005.)

Humans successfully mastered flight a century ago, yet the scientific understanding of low speed, small vehicle flight regimes is limited. The theory, practice and tools of aerodynamic flight mechanics, theoretical/experimental/computational fluid dynamics, aero-structural dynamics, and flight controller design currently used for large-scale vehicles seem to be of only limited use for development of small agile air vehicles operating at low speed in confined airspace. Aerodynamic flight agility remains a challenging and an elusive capability at these small scales. Even assuming that the technology hurdles will be overcome, aerodynamic flight agility is of limited use without comparable guidance agility: the ability to process sensory information and initiate maneuvers sufficiently fast to exploit the aerodynamic agility. Imagine a scenario in which the driver of an automobile negotiating an obstacle course is blindfolded, following a passenger's verbal instructions. A tuned sports car, quick responses and honed driving skills are irrelevant if the passenger's instructions are slow or imprecise. Moving safely at speed in a confined space requires the ability to detect an obstacle, assess relative motion and determine an appropriate response in sufficient time for the vehicle to accomplish the commanded maneuver. A sluggish vehicle has no need of fast sensory processing; an agile vehicle has an absolute requirement for fast, context appropriate sensory processing.

Since managing swarms of agile air vehicles in confined airspace will quickly exceed the abilities of a remote human operator, substantial autonomy is essential. The political, ethical, and moral issues associated with the use of autonomous systems in warfare will be debated long after the technology hurdles to their production have been overcome. Putting those issues aside for discussion in another forum, effective covert operation of unmanned systems in confined environments requires low-level autonomy for flight stabilization and successively higher levels of autonomy using on-board sensing for collision avoidance and local guidance. That is, a MAV will utilize its onboard guidance and control system for controlled agile maneuvering and for establishing feasible paths through an unknown and dynamic obstacle cluttered airspace. Given the high probability of communication dropout in urban canyons, some level of autonomous decision making capability is required. During pursuit of a group of fleeing vehicles a MAV swarm experiencing loss of communication with the operator will have to make real-time decisions on which vehicles to pursue if the fleeing group splits. (Abatti, 2005 discusses other operational issues associated with MAVs.)

Another challenge arises from the fact that humans occupy a spatiotemporal world that is dictated by our size, essentially terrestrial animal body-form, vision-dominated primate ancestry and our resulting sensory system capabilities/limitations. Extrapolation of that human-centric frame-of-reference to the design of MAVs the size of small bats, birds or insects is probably not desirable. Biology studies of the past century suggests these small animals not only occupy physical environments that are foreign to humans, but that they sense and

perceive those environment in ways humans have difficulty comprehending and never experience directly. By analogy, dogs appear to inhabit a world of smells the complexity of which is at least as rich as that of the visual world associated with human vision. That world of odors has only been marginally sampled by human chemo-sensing devices and has never been characterized into a picture three dimensional spatial awareness experienced by the animal. MAVs are envisioned to become agents of human operators to achieve human motivated purposes, not as artificial insects, birds or bats. The degree to which the sensing and perception of flying animals should become the foundation for agile autonomous MAV design is an open question that has only begun to be addressed.

Two broad areas of exploration of biological sensing can be defined: one area involves sensing for operational considerations such as biological or chemical agent detection, vehicle tracking, even for detection and identification of humans; another area, and the principle focus for this paper, involves sensing required to operate within confined airspace. These areas are by no means mutually exclusive for animals, as evidenced by echolocating bats that utilize their sonar for detecting and intercepting prey as well as for navigation and collision avoidance in dark caves. Given the limited payload capacities of MAVs, multifunctional sensors are certainly desirable and probably required. Unfortunately, using the same sensor for flight control and for providing operational data presents significant challenges to the system designer. Consider a camera providing some measure of body motion based on optic flow to augment an onboard inertial navigation system. In the absence of a global frame of reference (e.g., loss of GPS), the optic flow enhanced inertial navigation solution will provide the vehicle with a local frame of reference for stabilizing body perturbations from wind gusts, for achieving steering commands to divert around an obstacle and for locating a potential target on the operator's tactical map. The first requires relatively high bandwidth but relatively low resolution sensing, sufficient to stabilize the body dynamics. The second may also require relatively high bandwidth, moderate resolution sensing to enable detection and avoidance of obstacles in a dynamic scenario. The last can tolerate somewhat lower bandwidth, but will require high resolution sensing, sufficient to be compatible with the operator's map resolution requirement. In a closed loop configuration in which an output from a camera is used to steer and stabilize the vehicle, the sensed kinematics nonlinearly couple with the dynamics that drive the vehicle and hence the camera's motion. This coupling can destabilize the vehicle response and introduce errors into the estimate of a target's position. While addressing this kind of dynamic coupling associated with guidance systems with only a few sensors is still an open research area in the controls community, insects seem to do quite well in integrating many sensors with relatively small nervous systems. Dragonflies engage in highly dynamic aerial pursuits (e.g., pursuer whole body responses to an fleeing animal's maneuver have been measured from video at less than 40msecs) using a guidance system that seems to be dominated by compound eyes which have low resolution but high motion sensitivity. Gaining insight into the principles by which this is accomplished in biological systems may open entirely new avenues for engineered guidance and flight control system design.

3.0   WHY LOOK TO BIOLOGY?

Arguably, tactical air intercept missiles are the most agile autonomous air vehicles yet developed. A reasonable baseline agile MAV guidance system design might therefore begin with application of current state-of-the-art missile guidance and control system methodologies. The design process is typically based upon the vehicle six degree-of-freedom rigid-body dynamics and intercept kinematics; a quasi-static aerodynamics model derived from simulation or wind-tunnel tests; computed or experimentally derived flexible body dynamics, sensor and actuator dynamics models; and often accounts for computational latencies and sensor noise. Since the resulting mathematical model is complex and, in any case, is known only imperfectly, it is usually simplified by making various assumptions that allow the relatively fast body

dynamics to be decoupled from the slower intercept kinematics. An inner-loop controller for the rigid-body dynamics uses sensed inertial body rotation rates and accelerations to compute commands to the fin actuators; it is typically bandwidth-limited to avoid exciting the body flexible dynamics and actuator dynamics. The outer-loop controller, a guidance law, computes commands to the inner-loop controller from estimated relative kinematics between the missile and its target. This estimate is typically provided by a dynamic filter that correlates seeker measurements of the relative motion with predicted motion based on an internal model of the target dynamics. In spite of extensive work on modeling of target dynamics, missile guidance estimators introduce potentially destabilizing latencies into the guidance system response when used in scenarios differing significantly from those assumed during the design process.

A MAV guidance system based on this approach exhibits a kind of compartmented functionality. Time or frequency-based separation into a relatively high-bandwidth inner-loop and a lower-bandwidth outer-loop requires that the physical response of the vehicle in its interactions with its surroundings be separable into slow and fast dynamics. While this natural separation is usual and physically justifiable in manned aircraft and large UAVs, it may not be applicable to SUAVs and MAVs which are expected to operate in close proximity to terrain, obstacles and other vehicles. In aggressive maneuvers in confined airspace, the relative kinematics between a MAV and other nearby objects may be as fast as its body dynamics; this to a degree only approached in the last few seconds of a missile intercept scenario. Imposing the usual separation of slow and fast dynamics on a MAV guidance system design (that is, reducing its guidance response bandwidth to mitigate coupling with its body dynamics) will result in stable but sluggish vehicles that have only limited capability to operate in confined airspace. (See Lin, 1991 or Zarchan, 2002 for more on missile guidance.)

Biological sensory response systems, while having some functional similarities with engineered systems, seem to have very different architectures. For example, insects appear to have relatively fast inner response loops dominated by mechanosensors, with slower outer response loops dominated by vision. However, it does not appear that biological sensory response systems are characterized by the relatively rigid separation of slow and fast dynamics typical of engineered flight control systems. The aforementioned body sensing system of dipterous insects is a case in point. Vision and mechanosensing are apparently used at all levels of a sensory response flight control system that is characterized by massive sensory interconnection and feedback. Certainly biologists have not yet resolved the detailed architecture and dynamics of any insect nervous system, but the behavioral and neurobiological work to date suggests much more coupling of sensorimotor system dynamics than is found in engineered systems.

Flying insects display a wide diversity of body morphologies, many of which are capable of impressive feats of aerobatic flight. Dragonflies, like many insects, have two pairs of membranous wings independently driven directly by flight muscles. Hoverflies, a kind of dipterous fly, have only a single pair of wings driven indirectly by muscles that rhythmically contract the thorax; the hind wings have become specialized as small body rotation sensors (halteres). Butterflies and moths have two pairs of wings that flap in synchrony, functioning effectively as a single pair of low aspect-ratio wings. Each group contains insects capable of hovering and highly maneuverable flight, apparently achieved by exploiting unsteady aerodynamics produced from precisely controlled wing kinematics. Compound eyes provide wide field-of-view motion sensitivity that, integrated with a variety of body mechanosensors (e.g., halteres in dipterous flies, antennae in moths, and perhaps sensors at the base of the wings themselves in those and other insects) and various proprioceptors and strain sensors distributed throughout the body, provide the necessary feedback for stable controlled flight. The compound eyes, often augmented by small simple eyes (ocelli), provide attitude reference information essential for level flight. The compound eyes also track small targets, often in specialized regions of higher acuity facets, providing the sensory feedback necessary for prey or mate pursuit, for predator evasion or with other sensory modalities for food localization. In addition to the vision system, chemoreceptors, especially in

the antennae but also localized in other body regions, and tactile sensory hairs distributed over the body provide insects with a nearly spherical field-of-regard sensing capability. (A large and growing literature on insect sensing exists: good places to start are McIver, 1985 for mechanosensing, and Warrant and Nilsson, 2006 for insect vision.)

Flying birds, ranging in size from tiny hummingbirds to eagles, likewise have impressive flight capabilities. Bird wings are feather covered, highly modified vertebrate forelimbs in which the wrist and finger bones are fused and reduced in size. The wings, which are deformable due to the elbow and wrist joints and elastic due to flexibility of the feathers, are powered by specialized pectoral and coracoid muscles attached to a deeply keeled sternum. Terns have high aspect-ratio wings and fly much like manmade aircraft while soaring but are capable of agile precise flight when picking small fish from the water surface. Eagles, with broad powerful wings, exploit thermals in extended soaring but are capable of aggressive controlled maneuvers in which the wings appear to become completely stalled during takeoff, landing, or prey capture. Falcons can plummet at high speed to snatch a small passerine bird from within a flock, while accurately maneuvering to avoid potentially crippling collisions with other birds in the flock. Hummingbirds, unlike other birds, exhibit insect-like wing kinematics during hover, completely reversing the upper and lower surfaces during a full wing stroke. Somewhat surprisingly, given the similarity in wing kinematics, unlike insects hummingbirds do not appear to generate lift on the recovery upstroke. All birds have vestibular organs providing body motion information that, perhaps with wing muscle load sensing and probably with input from vision motion sensing, allow for stable controlled flight. High vision acuity in the fovea of the vertebrate eye, cued from peripheral vision motion sensing and other senses, provides vision-dominated sensory systems that allow hummingbirds to feed on flower nectar while hovering and swifts to feed on insects in flight. The well known auditory capabilities of owls represent an elaboration of a sensory modality that is important in all birds.

Bats, the third and evolutionarily most recent example of extant flying organisms, demonstrate flight maneuver capabilities that are at least the equal of those of insects and birds. The wings are skin membrane covered, highly modified vertebrate forelimbs in which the fingers are greatly elongated and flexible, comprising up to half the wing span in some bats. Bat wings are actively deformable from the elbow, wrist, and finger joints and from the aerodynamic loading of an extraordinarily flexible anisotropic membrane covering limb bones and flexible fingers. Flying foxes, with wingspans approaching a meter, locate and feed on fruit in tropical tree canopies. Nectar-feeding bats exhibit hovering behaviors and capabilities comparable to hummingbirds or hoverflies but with dramatic deformations of the wing shape during each stroke. Insectivorous bats likewise exhibit in-flight feeding behaviors comparable to dragonflies, swifts and kestrels but with very different wing motions. Like birds, bats have vestibular organs providing body motion information that, with wing muscle load sensing and probably with input from vision motion sensing, allows for stable controlled flight. High vision acuity in the fovea of the bat's typical vertebrate eye, cued from peripheral vision motion sensing, provides vision-dominated sensory systems in old world bats and augments the extraordinary echolocation system of new world bats. Like most other mammals, hearing and olfaction are important sensory modalities for all bats.

4.0   EXPLORING BIOLOGICAL FLIGHT

In the quest for principles upon which to base the design of vehicles with agile autonomy comparable to insects, birds, and bats, several areas of potential biology contributions emerge. The most obvious of these is to understand aeroelastic, flapping wing flight at low Reynolds numbers. Significant open questions remain in the fluid dynamics associated with flapping wing motions at high angles of attack. Studies of the detailed three-dimensional wing kinematics, flow visualization and/or limited force measurements have been made for

several insects, several birds, and a few bats. Experiments with rotating or flapping scale model insect or hummingbird wings indicate that quasi-steady forces produced during a high angle-of-attack wing stroke are augmented by a stable leading edge vortex that increases circulation around the wing. Rapid spanwise rotation at the end of each stroke in small insects produces force spikes that appear be used for maneuvering. Unlike insect wings, bird wings can be actively morphed to give the same bird soaring capabilities when extended and high speed dives when tucked. The degree to which birds exploit this wing morphing for flight stabilization and control has not been determined, though casual observation and some video studies suggest it is a common behavior. As with insects and bats, aeroelasticity allows for passive gust rejection, although again studies quantifying the relative contribution of other aerodynamic force producing mechanisms have yet to be made. There is some evidence that surface topology and texture of hummingbird wings makes significant contributions to net force production during the wing stroke. Bats, with their highly morphable wings, have received far less study than insects and birds but recent elegant wind tunnel experiments have produced qualitative flow visualization that shows the incredible complexity of flows associated with bat flight. Videos of bats during tight turns show extensive wing morphing, probably actively controlled by the animal as well as passively produced by aerodynamic and inertial forces. The importance of this morphing to the flight stability and control of the bat is the subject of current study. (Azuma, 2006 provides an interesting overview of animal flight.)

Another area of potential contribution is to explore the sensory-rich, multi-scale feedback associated with animal flight. Insects are literally covered with sensors that, with the limited processing available from the few hundred thousand neurons in an insect brain, allow these animals to fly with damaged wings, order of body mass payloads (e.g., foraging bees with a load of pollen, blood satiated female mosquitoes) and in gusty wind conditions. Flies have modified hind wings, the halteres, that flap in antiphase with the aerodynamic wings and respond to Coriolis forces generated by body rotations. Patches of strain sensors at the base of the halteres provide signals that directly modulate the flight muscles controlling wing kinematics; this may be somewhat analogous to the rate feedback from gyros used for providing rate stability in aircraft autopilots. Augmenting this, the compound eyes sense optic flow, the apparent image motion produced from body rotation and translation, and provide signals that modulate the haltere feedback to the flight control muscles. Coordination of the two wings and input from other body sensory modalities occurs at the thoracic ganglia and with sensory input from the head sensors in the subpharyngeal ganglion. Other insects similarly integrate mechanosensory signals (e.g., antenna as body rotation sensors in moths and butterflies) with vision and other sensory modalities to produce stable yet agile flight capabilities. (See for example Dudley, 2000 and Burrows, 1996.)

Birds and bats have flight control sensory systems elaborated from the basic vertebrate sensor suite. Both have vestibular organs providing attitude and body rotational feedback that apparently is complemented by input from the vision system, particularly peripheral motion sensing, in the brain cerebellum. Muscle strain sensors potentially provide both groups of animals with the ability to sense dynamic wing loading, which could be useful for both local active damping of wing motion to complement the passive aerodynamic damping from wing flexibility and as another sensory feedback for controlling the wing kinematics. Bird feathers contain sensory neurons at their bases providing tactile sensing that may potentially be exploited as additional flight control feedback. Videos captured from on board cameras of soaring and landing eagles show deployment of a row of leading edge covert feathers, presumably concurrent with the shift in stagnation point associated with an incipient wing stall. Whether this is a passive or active aerodynamic mechanism roughly analogous to leading edge flaps on aircraft or a sensory mechanism employed by the bird is unknown and the subject of current study. Bats have small sensory hairs, a few millimeters in length, distributed in patches over the wing surface. Studies are underway to investigate the roles of this sensory modality, if any, in flight stabilization.

At the other end of the sensory-response chain, biological flight control involves multiple complementary

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actuators, the flight power and control muscles. In all organisms, limb movement is produced by muscles that work in pairs since muscles can only produce force during contraction. Dragonflies, locusts, and many other insects utilize muscles that directly drive the wings. The wing kinematics, including in-plane and out-of-plane motion with spanwise rotation during and at the end of the wing strokes, are controlled by precise timing and modulation of several muscles. Like most body muscles, these contractions are controlled by direct innervation from motor neurons. Dipterous flies and many other small bodied insects use orthogonal pairs of power muscles that produce alternating dorso-ventral and longitudinal flexure of the thorax from rhythmic contractions similar to heart muscle activity. The wings, attached to the thorax with a complex segmented hinge structure, beat passively with the thoracic contractions. Very small neuronally innervated muscles attach to the hinge segments and, in concert, change the mechanical properties of the hinge to produce the three-dimensional wing rotational kinematics. Insects also use body musculature to control abdomen, head, and leg postures during flight, presumably contributing inertial as well as additional aerodynamic forces to produce maneuvers. (See Dudley, 2000 for an in-depth description of insect flight.)

Birds and bats have neuronally innervated skeletal musculature modified from the typical vertebrate plan. Powerful pectoral muscles provide the downstroke and other thoracic and upper forelimb muscles produce the balance of wing rotational kinematics used for flight. Both birds and bats, unlike insects, can also utilize the forearm musculature to actively extend and retract the wing and to change both the chordwise and spanwise shape. Bats, in particular, have astounding control over the three-dimensional wing shape at all phases of the wing stroke. Birds produce yaw forces through active control of the shape and position of the tail. At least some bats have membranes attached to the legs that may similarly produce lateral stability and control. Like insects, bats and birds can actively use body posture to augment aerodynamic flight control from the wings. Given the large number of muscles controlling large degree-of-freedom force effectors, substantial control redundancy is available to both animal groups.

In addition to precise agile flight, these musculoskeletal wing systems exhibit impressive amounts of robustness. Bats with large tears in their wing membranes or with young attached to their abdomens appear to fly quite normally. Some small birds nearly double their mass just prior to laying eggs; others lose significant wing feathers to molt or near escapes from predators and still are capable of seemingly normal flight. Dragonflies experiencing the loss of half of one wing, bees with legs packed with pollen, butterflies or moths with torn and frayed wings likewise are capable of apparently normal flight. These largely unstudied, mostly anecdotal observations suggest that biological flight control systems, which consist of structural, passive dynamic, and active sensorimotor control mechanisms, have robustness and performance characteristics that would be very desirable and probably essential for agile autonomous MAVs.

As human pilots attest, agile flight and flight in confined airspace require wide field-of-view situational awareness. Insects possess paired compound eyes that, in several insect groups, together yield a nearly completely spherical field-of-view. In addition to wide field optic flow sensing for flight stability, specialized vision circuits detect and track small objects moving relative to the background. Since compound eye resolution is poor, limited for the most part by the facet instantaneous fields-of-view and inter-facet spacing, insects exploit vision motion processing as a dominant sensory modality for aerial prey or mate pursuit, predator and obstacle avoidance, local navigation, visual odometry and food source detection. Some insects have regions of higher visual acuity which allow more precise object tracking. Since the eyes are fixed to the head, gaze stabilization and control is effected by control of head to body posture with neck muscles. Complementing vision, insects employ olfaction and taste chemoreceptors as well as tactile hair cells to obtain a three-dimensional information source for interacting with their surroundings.

Similarly, birds and bats employ relatively wide field-of-view eyes for the same sorts of behaviors, though

exploiting very high resolution fovea, multiple in birds of prey, to obtain detailed shape and texture imaging of their surroundings. Bats, like other mammals, use small muscles to move the eyes in their sockets, complemented with head movement controlled by neck musculature, to track small rapidly moving objects. Given the limited mobility of their eyes, birds utilize head motion for gaze stabilization and object tracking similar to insects. Birds have acute auditory sensing; barn owls, especially, are well known for being able to use their hearing to locate and precisely track small mammals. New world bats, of course, use high frequency echolocation both for navigation in caves or attics and for detecting and tracking insect prey on the wing.

All animals exploit movement to enhance sensing. Flying insects, birds and bats require depth perception to negotiate confined airspace. Although binocular vision may contribute to varying degrees, translation induced parallax, suitably filtered to remove the apparent motion induced by body rotations, is probably the primary source of relative distances and closing velocities to surrounding objects that are required for pursuit or avoidance behavior. Recent elegant studies on honeybees suggest that passive ranging from small amplitude lateral casting during forward flight may be part of the animals' height regulation mechanisms (Baird, et al., 2006). Similarly, stereotyped lateral motion just prior to landing on a vertical surface may give bees range information for precise landings.

5.0   UNDERSTANDING BIOLOGICAL FLIGHT

The first, and perhaps the greatest challenge to engineers and other nonbiologists who attempt to look for biological solutions to their problems of interest stems from differences in training, methodologies, tools, and viewpoints. Engineering and most of the other physical sciences lend themselves to somewhat reductionist approaches for both analysis and synthesis. Complex engineered systems are built from components integrated into functional subsystems that are, in turn, built into operational systems. Considerable effort and expense is required to verify that performance meets specifications and to validate the acceptable operational regime for the system. Efforts to develop system design methodologies that yield performance and stability guarantees are very active areas of control theory and software systems research. Powerful techniques exist for analysis at the component or subsystem level; unfortunately, these do not often scale to the system level.

Biology as a science consists of a suite of interrelated disciplines each with specific terminology and a particular foundation of theory and practice. Just as modern aeronautical engineering is built on a base of dynamics, mathematics, fluid dynamics, structural dynamics, and computer science; so systems biology is built on fundamental concepts from evolution, ecology, behavior, anatomy, physiology, developmental biology, genetics and statistical analysis. Unlike many engineering fields, no unified suite of mathematically based physical laws has yet been developed for any biology discipline, much less for the entire science area. This makes biology seem to be observational, heuristic, and a bit of a soft science to many practicing physicists, chemists, and engineers. Of course, mathematical analysis, particularly statistics, has become an essential tool for biologists who must digest large amounts of observational data into coherent concepts from which biological principles may be deduced. Dynamical models in ecology, population dynamics, genetics, biomechanics, biochemistry and many other areas has become more important in the past half century but most still lag in predictive capabilities when compared with those of the physical sciences.

It is important to not overly emphasize this lack of mathematical unity as a limitation of biology as a science. For one thing, while the mathematical foundations for many engineering disciplines are well established, the area of engineered complex systems lacks mathematical unity and many of the applicable mathematical tools are *ad hoc*. Since all biological response, even locally, involves complex sensory/processing/actuation responses the mathematical tools simply do not exist to reliably characterize them. More importantly, theories

associated with genetics, biochemistry, developmental biology, ecology, and evolution provide a unifying foundation for the seemingly disparate disciplines of biology. Thus biologists can study moth, hummingbird, and small bat flight with an appreciation of the developmental, ecological, and evolutionary pressures influencing and constraining the apparently different solutions to flapping flight at similar conditions. These biological studies are essential complements for the fluid dynamics, flight mechanics, control systems and other studies performed by engineers and physicists to ultimately yield a complete picture of biological flight.

Issues of scale dominate any serious study of biological sensorimotor systems. An amazing diversity of organism types inhabits our world, from bacteria and other single celled organisms through the many types of multicellular animals. In looking for biological prototypes for engineered systems, this diversity offers a sometimes staggering array of potential sources of inspiration. The mechanisms of natural selection, working upon the variation produced by processes of reproduction and inheritance, yield organisms that, to varying degrees, are both adapted to their particular modes of life and robust to variations in their respective environments. Any species exhibits significant variation among individuals, very loosely analogous to an automaker's entire range of passenger vehicles rather than to the small differences among cars of a particular model. A species' ability to persist over time in the face of changes in habitat, fauna, flora, or climate largely results from this variation. Hence, adaptability, when used in reference to a species, implies that sufficient stable variation exists for the species to tolerate substantial selection pressures produced from these or other ecological forces. Thus, biology offers a large range of viable solutions, not necessarily highly optimized ones. In fact, even in species exhibiting high degrees of ecological or behavioral specialization significant individual variations exist; these variations are typically much greater than would be tolerated in engineered systems. The extent to which these variations are a casual byproducts of imprecise developmental mechanisms versus the products of evolutionary mechanisms essential for species robustness has not been systematically investigated in any organism. This provides a cautionary note for those pursuing biomimicry, direct replication of biological features: essential aspects of those biological features may be driven by secondary characteristics or functions unrelated to the features' primary functions. The bat wing, with all of its elegant modifications for flight, is an obvious example. It is derived from a typical vertebrate forelimb with all of the associated musculature, skeletal, and neuronal architectural characteristics that were originally developed for terrestrial or aboreal locomotion. That is, it was not designed for propulsive flight *a priori* as an engineered device might be, but was modified from other structures that originated for other functions. (Gerhart and Kirschner, 1997 provide an in-depth but accessible discussion on the interplay of biochemistry, genetics and embryology in animal evolution; Wagner, 2005 describes biological concepts of evolvability and robustness.)

Paradoxically, along with these variations, underlying similarities unite organisms in ways that may seem mysterious to nonbiologists. Living organisms, unicellular and multicellular, share common structural, biochemical, genetic and organizational processes. These processes function to various degrees throughout an organism's life during all interactions with the local environment. All parts of any multicellular organism (organelles, cells, tissues, organs, and organ systems) exhibit these processes individually as components and collectively as subsystems comprising the entire organism. These processes also function continuously during each stage of a multicellular organism's development, from cell through embryo through adult. So flying insects and birds with similar flight capabilities have eyes of very different structures and different functional capabilities; that were evolved through different phylogenetic histories; and that have been fixed into their respective adult forms by different developmental processes. Because organisms exhibit such integration, reductionist methods of component analysis are not, in general, adequate for understanding biological sensorimotor functionality. For example, the morphology, phototransduction, and neuronal characteristics of the eye comprise only a limited part of an animal's vision system, which requires the associated brain neuronal circuitry, propriosensory mechanisms and musculoskeletal system to function as a sensor! (See

Gerhart and Kirschner, 1997 for additional discussion and examples.)

Another aspect of scale arises from the fact that flying animals occupy a large range of body sizes. The smallest insects, such as midges and fruitflies, exhibit flight capabilities similar to bats and birds that are seven orders of magnitude larger in body mass. The sciences of flight mechanics and aerodynamics, developed for steady flight at size scales appropriate to manned vehicles with Reynolds numbers in the millions, are limited in their abilities to describe animal flapping flight at Reynolds numbers of a few thousand to hundreds. Unsteady aerodynamic mechanisms that seem to be exploited in the maneuvering flight of small animals are typically minimized, often at great expense, in the design of aircraft. While the utility of such mechanisms for small air vehicles is yet to be quantified, it is clear that animal sensorimotor flight control systems actively utilize them even during what we might think of as steady flight. The questions of whether and how much these mechanisms should be designed into small air vehicles have not yet been answered. Results to date from biology suggest that their use will require rethinking the sensory and flight control suites currently employed on engineered small air vehicles.

These lessons suggest that comparison of closely related animals of different sizes will be useful for developing a science of biological flight. Likewise, comparison and contrasts of much more distantly related but ecologically and behaviorally similar animals, for example hummingbirds, hawkmoths, and small nectar feeding bats, will yield insight into the principles exploited by animals for maneuvering flight. Some of these principles are likely to be of use in the design of agile autonomous small air vehicles. Some may turn out to be useful only in the context of understanding the various constraints and influences imposed by biological pressures. Distinguishing these principles may turn out to be the most difficult task associated with biologically inspired flight and will require close collaborations of biologists and engineers. It is important to note that most biologists, even when conducting controlled experiments on particular features of their study animals, appreciate the complexity of factors associated with biological system responses and are usually careful to qualify their conclusions based on the artificial conditions imposed by the methods of the studies. Productive engineer and biologist collaborations usually require a fair dose of patience on both sides and rarely emerge over night!

6.0   BIOMIMICRY OR BIOLOGICAL-INSPIRATION

Mimicry of biological systems, in the form of precise mathematical or physical dynamical modeling, is yielding impressive insight into the underlying functionality and mechanisms of the biological systems themselves. Robot devices that capture insect leg kinematics provide the foundation for studies of the sensorimotor mechanisms of walking with six legs (Ritzmann, et al., 2004). Computational analyses of insect flapping wing flight complement experiments with model wings flapping or rotating at appropriate Reynolds numbers. Such studies are allowing characterization and quantification of the underlying aerodynamic mechanisms associated with flapping flight (Azuma, 2006). Analog and digital models of insect vision motion processing provide useful tools for studying the role of optic flow processing in biological flight stabilization and local guidance. While these and other mimicked biological features are being explored for direct application to engineered systems, the payoffs have thus far been much more limited than for gaining insight into the biology.

Biological inspiration has an impressive and long history, extending perhaps to the roots of human technology. The physical and biological world provided our ancestors with inspiration for techniques and tools that allowed them to extend their physical capabilities. Methods of earliest human agriculture, exploitation of fire for clearing land and cooking meat and cooperative hunting methods all emerged at a time

when humans were bound into the same kinds of ecological cycles as other similar-sized savannah dwelling animals and were, therefore, intimately familiar with their natural surroundings. Although mankind is generally removed from that world by today's technologies, all of the human pharmaceutical industry, current medical practice and modern agriculture are founded on our understanding of biology. Thus, the study of biological locomotion seems to be a natural route to expansion of the capabilities of flying robots. Ironically then, the most universal technologies associated with human locomotion, the wheel, the rigid wing and the rotating propeller, are not found in nature. This irony provides a cautionary note that human engineered systems may have attributes and constraints that, ultimately, preclude biological solutions.

To date, legged robots or flapping wing air vehicles exist primarily as laboratory experimental devices. Roboticists working with biologists have designed wheel-legged robots that, with a single driving motor, clever transmissions, and a jointed body, are capable of climbing stairs and negotiating uneven terrain using rotational leg kinematics that are inspired from studies of the insect three-legged walking gait (Ritzmann, et al., 2004). Another engineering team designed a flying micro-air vehicle that, using a rigid forward wing with two clapping tail wings, was originally inspired from an unsteady aerodynamic mechanism first identified in certain flying insects, but that operates as a system much more like swimming fish than an insect (Jones, et al., 2005). Other engineers in collaboration with insect vision neurophysiologists have explored the use of paired UV and green light sensitive photodiodes driving a simple analog comparator circuit to produce pitch and roll attitude stability in a model aircraft. The prototype device concept, functionally analogous to dragonfly ocelli, offers the potential for a scalable, low cost attitude stability system for MAVs. Another group of engineers, also working with insect vision neurophysiologists, is developing a concept for a local guidance and collision avoidance system that is inspired by studies of insect optic flow processing (Humbert, et al., 2005 and Shoemaker, et al., 2005).

It is intriguing to imagine some of these or other similar efforts in the not to distant future yielding the first demonstration of a biologically inspired agile autonomous MAV. Whether such a system will utilize the wing kinematics of insects, birds, bats, or more conventional aerodynamic mechanisms remains to be seen. The degree to which such a system will require the complex sensorimotor integration that seems to characterize biological systems is also yet to be determined. What can be stated with some confidence is that, given the limitations of current state-of-the-art MAV flight technologies, studies of biological flight will yield insight into propulsive flight at these small scales that will almost certainly accelerate the development of agile autonomous MAVs.

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Issues of Scale in Agile Micro Autonomous Systems

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The quest for micro autonomous systems (MAS) is taking us from the realms of science and engineering, as with the University of California at Berkeley micro mechanical flying insect, to areas that would have been the realm of science fiction just a few years ago, as in Darpa's Nano Air Vehicle program. Emboldened by advances in micro-scale technologies and inspired by insight into the mechanisms associated with biological locomotion, eventual realization of bird or insect size autonomous robots seems certain. Among the many technical challenges, issues associated with integration of MAS into complex human-directed information networks, in particular issues of autonomous sensory-response architectures for systems with multi-scale dynamics, may prove to be the largest hurdles. This paper speculates on the existence of a fundamental characteristic of autonomous systems that may underlie those hurdles.

I.   Introduction

HUMAN engineered systems increasingly rely on automation to enhance performance, provide fault tolerance and allow the operator to concentrate on high-level decisions as opposed to low-level motor control tasks. These systems are designed to be responsive to human-generated commands but at the same time robust to disturbances that may require corrections several orders of magnitude faster than human response times. Advanced fighter aircraft, for example, maneuver at the edge of human sensory-response capabilities by having autopilots that stabilize the aircraft through operating regimes beyond the capabilities of direct human control. Artificial limits on the aircraft operational envelope, which are imposed on the aircraft performance to accommodate the limitations of human physiology and sensory-response capabilities, are made necessary by the critical role of the human as pilot of the vehicle. In effect, the human operated fighter aircraft has an outer-loop/inner-loop flight control system in which the pilot provides the sensing, decision processing and command functions to the inner-loop autopilot which, in turn, stabilizes the aircraft flight during maneuvers. This time- or frequency-based separation into a relatively high-bandwidth inner stabilization loop and a lower-bandwidth outer command loop is a common control system architecture that requires the physical response of the vehicle in its interactions with its surroundings to be separable into fast and slow dynamics. While this separation is usual and physically justified in manned aircraft and large UAVs, it may not be applicable to agile MAS capable of aggressive maneuvers in confined space where the relative kinematics between a MAS and other nearby objects may require a response bandwidth on the same time scale as stabilization of the MAS body dynamics. Imposing the usual separation of slow and fast dynamics on a MAS design, for example by reducing its response bandwidth to mitigate coupling with its body dynamics, will result in stable but sluggish vehicles that have only limited agility. Such is the case with existing MAS.

Of course, the vision is for MAS to achieve or even exceed the agility, performance and robustness of living systems. We entertain notions of sending small groups of MAS into urban centers of conflict to search for, detect and engage hostile targets with minimal collateral damage to humans or the urban infrastructure (Figure 1). These flocks of engineered vehicles would have the flight capabilities of insects, birds or bats but be under the overall supervision of one or more human operators. That is, the MAS would require significant autonomous guidance capabilities to negotiate the confined and high uncertainty environment while requiring positive human control of mission-level objectives, target confirmation and target engagement. Putting aside the various ethical issues of employing autonomous lethal agents, the challenges imposed by the multi-scale dynamics inherent in this scenario are large. Human command and decision processes may span minutes to days, while the dynamics associated with micro-scale flight may evolve over milliseconds. Errors at the human decision level have obvious potential to impact the overall system performance, from failure to perceive and act upon a critical piece of information to prosecuting the wrong target. Similarly, errors at the MAS level propagate upward to the human decision level, producing gaps

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in critical information or distorting the context of otherwise correct information. The emergent consequences of these different scales of errors are impossible to predict with our current system modeling tools. Thus, consequences of a MAS's erroneous positive response to a benign chemical signature may be negligible, merely resulting in the vehicle flying into a nearby window and disrupting a peaceful family dinner. Alternatively the consequences may be tragic, prompting escalation of a minor into a major conflict. Unfortunately, our capabilities of engineering MAS seem to be outpacing our understanding of how to incorporate them into fault resistant human decision networks.

Figure 1. Group of agile MAS entering an urban canyon

This paper takes the perspective that agile MAS with their layers of human supervision represent complex, highly nonlinear multi-scale dynamical systems. After a brief discussion of some issues of scale for such systems and current research investigating those issues, the paper will focus on the idea of autonomy associated with multi-scale dynamical systems. Agile MAS currently exist only in nature (i.e., insects, birds, bats). Consequently, the paper will consider autonomy in manmade MAS from a biological perspective. That is, it will speculate that functional system characteristics associated with the capabilities of living flying organisms may require levels of response variation and flexibility that are not associated with, and perhaps will not be tolerated in manmade critical systems. Although this paper will not directly address questions of ethics associated with the deployment of critical autonomous systems, it will attempt to provide some insight into how those important questions may naturally emerge when any degree of robustness is imposed as a design criterion for manmade agile autonomous systems.

II. Automatic Control

For present purposes, 'dynamical systems' can be thought of as systems which evolve through time. Mathematically their behavior can be described by combinations of differential or difference equations. In addition to familiar examples such as objects in motion, fluid flow and heat flow, this definition also covers modern 'information networks' such as human decision systems, the internet, networked communication systems, and command & control systems.

Dynamical systems which evolve over a narrow time scale range can be characterized using a rich body of descriptive and computational mathematics. An automobile operating on cruise control provides a familiar example. A complete description of all of the dynamics associated with engine, friction and aerodynamic forces is of extremely high order. It involves time scales ranging from those of the combustion processes, motion induced aerodynamic turbulence and heat flux during severe braking to those of the vehicle accelerator response, certainly several orders of magnitude. While on cruise control however, the vehicle accelerates or decelerates in response to road grade or wind variations to maintain a relatively constant speed. In this cruise mode, the dominant dynamics associated with the vehicle motion are adequately described as a compact set of 3 linear 1st order differential equations with a time constant on the order of seconds. Actually most familiar manmade systems, whether home heating/cooling systems, home power generators or automatically piloted commercial aircraft are designed to exhibit this relatively linear, narrow bandwidth response.

Some manmade systems do not lend themselves to such a compact mathematical description. The most agile air vehicles currently produced, tactical air intercept homing missiles, provide an interesting example of a wide-scale dynamical system. A reasonably minimal description of such a missile during the later phases of a target engagement would be of relatively high order and highly nonlinear. These dynamics would include the target detection and warhead event, associated with fractions of millisecond time constants; the vehicle rigid body dynamics, having 10s of millisecond time constants; and the intercept kinematics, having 100s of millisecond time constants. As is typical for such systems, during the design process these different time scale dynamics are treated separately. The warhead and target detection system are designed separately from the missile autopilot; the autopilot is designed to stabilize the body rotational dynamics and to achieve the guidance system commanded accelerations; and the guidance system is designed generate acceleration commands to steer the missile close to an intercept with the target.[1]

Continuing with this example, a missile developed to intercept high agility targets requires guidance systems capable of high bandwidth response (i.e., small time constants). This, in turn, requires that the autopilot have a much higher bandwidth response, typically with 0.2 or smaller time constants than that of the guidance system. Of course the airframe itself must be capable of achieving such small response time constants. For example, consider how fast you can move a long flexible fishing rod versus a short stiff one. Move the long flexible rod relatively slowly and the rod tip will follow the hand motion. Move it more quickly and the tip motion will be out of phase with the hand motion. The short stiff rod, however, may be moved as quickly as you can with minimal deflection. Likewise, the missile airframe must be stiff enough to produce the accelerations required to intercept the target. The design of a wide bandwidth system such this challenges the capabilities of the tools of automatic control.[2]

Automatically controlled dynamical systems have become pervasive in our technology-based society. From climate control systems in homes and buildings to automated aircraft landing systems, the notion of manmade systems responding to changing conditions on their own has become a familiar one. The idea of sensing some error in desired response and generating a correction proportional to that error is intuitive and has its origin in antiquity. A textbook example is that of the mechanical governor of James Watt's steam engine. As engine speed increases/decreases, a spinning pendulum device decreases/increases steam to the engine through a mechanical linkage. This allows the engine to respond to varying loads with consistent performance without operator intervention, a measure of system 'performance', and prevents the engine from exceeding its cycling limits if the load is abruptly changed, a measure of system 'robustness'. The rate at which the speed of the governed engine can accommodate load variations is a measure of its response bandwidth. Again, it is intuitive that beyond a threshold rate, very rapid changes to the engine load will exceed the response capabilities of the engine system. For example, this limited response may result from a response latency or time delay in steam flow to increase in engine speed. These characteristics of performance, robustness, bandwidth, and time delay sensitivity comprise some of the principle figures of merit for any controlled dynamical system. This example also illustrates another key feature of most automatically controlled dynamical systems: that the operator interacts with the system through modulation of the controller. That is, the engine speed is regulated by adjusting the governor rather than directly adjusting the steam flow. Thus, the human operator can be thought of as an 'outer loop controller', modifying the speed range of the engine based on his own sensing processes, with the actual speed of the engine regulated by the 'inner loop controller', the governor/steam regulator.

Manmade automatically controlled machines are usually designed to provide a fairly linear response to commands, however nonlinear the underlying dynamics may be. In effect, the controller cancels the undesirable dynamics and replaces them with a desired linear dynamical response. Image stabilization in modern digital point and shoot cameras provides a rather familiar example of this cancellation of dynamics. Photographer motion is sensed and compensated through any of various mechanisms so that much of the motion-induced blur is removed from the resulting image. Any photographer motion beyond the bandwidth of the image stabilization system will appear as image blur.

In the early half of the 20th century, mathematicians such as Norbert Wiener and colleagues established information and decision theory as a foundation for development of dynamics and control systems theory and methodology.[3] Beginning with rudimentary notions of feedback (e.g., the modulation of dynamics based on sensed signals in Gibb's mechanical governor) the latter half of the 20th century saw the birth and maturation of theories of linear multivariable, linear robust, stochastic linear, adaptive, nonlinear, distributed parameter and cooperative control, to name only a few categories. Based on the mathematics of linear algebra, set theory, real and complex analysis, optimization and so on, the methodologies and tools available for control system design have become essential to the operation of many engineered systems from compact disc players to commercial aircraft.[4]

These tools are not without their limitations. To continue the example of a tactical air intercept missile, separation of the control design into an inner autopilot stabilization loop and an outer guidance intercept loop

imposes an artificial limitation on the missile intercept performance. With a high order dynamics description of the coupled intercept kinematics and vehicle body dynamics of sufficient fidelity, a designer can produce a very high-bandwidth controller that directly computes missile fin deflection commands from measurements of target maneuver. Unfortunately, such a controller is very brittle in the sense that its response degrades or even becomes unstable in the presence of inevitable errors in the dynamics model, unmodeled time delay, unmodeled high-frequency dynamics, unpredictable disturbances, uncharacterized sensor noise, and target maneuver uncertainties. Throughout the 1990's, many publications described various attempts to design integrated guidance and control systems that recovered some of the response bandwidth sacrificed with inner-outer-loop designs. Few of these approaches have been successful in practice for reasons of high design cost (e.g., requiring high-bandwidth actuators, extensive tests to produce accurate dynamics models, low noise sensors, low airframe manufacturing tolerances, etc.) and lack of real-world robustness, the latter due to a combination of control methodology limitations and the realities of operation in stressing environments.[5]

Much of the research on integrated guidance and control, and wide-bandwidth control in general, focuses on increasing performance rather than robustness. The field of adaptive control instead focuses on increased robustness, or equivalently expansion of the performance regime of the system. Adaptive controllers implicitly or explicitly learn the unmodeled or unknown system dynamics and modify the control signal to accommodate their impact on the desired system response. Early adaptive control methods simply adjusted the controller gain to zero the error between desired and actual system output responses. More recent adaptive control schemes inject an additional control signal to preserve a system's nominal response in the face of uncertainty or disturbances. Some of the most interesting and useful advances in control theory have occurred in adaptive control theory in the past ten-fifteen years. Although useful in process control applications such as chemical processing and plants, the aerospace industry has been slow to accept adaptive control. In the past decade however, newer methods for design of adaptive controllers have been applied to manned experimental aircraft and precision guided bombs.[6,7]

While manmade automatic control systems are common, manmade autonomous systems are not. The reasons for this require some explanation of the differences between the two concepts. Essentially all automatic control systems are designed to produce desired response in operatation over rather narrow operating regimes. This may be accomplished through a combination of limiting the response bandwidth (i.e., essentially the closed loop systems ignores disturbances, inputs and noise beyond its response bandwidth) and *ad hoc* limits imposed on the system response (e.g., min/max thermostat temperatures, RPM limiters on motor control systems, physical stops on actuators, cut-out switches, etc.). These features allow the automatic control system to operate without human intervention for long periods, delivering predictable response in the face of outside disturbances; the automobile cruise control comes to mind.

In casual usage, autonomy implies a level of response robustness beyond that associated with more familiar automatic control systems, whether adaptive or not. For example, a commercial aircraft autopilot allows steady cruise, climb or descent in the presence of varying winds, but an autonomous landing system must allow the aircraft to negotiate the far more uncertain wind conditions near the ground. Note, however that these kinds of 'autonomous' systems are still designed for very predictable response in the presence of an expanded range of uncertain, but reasonably characterizable dynamic disturbance conditions. For present purposes, these kinds of systems will be considered an elaboration of automatic control systems.

The concept of autonomy as used in this paper is illustrated by examples from the science fiction genre of motion pictures: the spacecraft computer Hal in the movie *2001: A Space Odyssey*, the cyber organisms in the *Terminator* movies, or the robot Sonny in the movie *I Robot*. These fictitious robots demonstrate both high levels of response robustness and similarly high levels of flexibility in response. That is, they vary their responses to be appropriate to the context of the current and anticipated situations in ways that seem very 'life-like'. These are systems that can be given a mission and allowed to respond as they will during the course of accomplishing the mission. This is a very different sort of behavior from that of an automatic control system, whether adaptive or not. And it is specifically this kind of behavior that is implied, whether intentionally or not, by many descriptions of MAS.[8]

To be a bit more specific, this concept of autonomy implies flexible and context-appropriate behavioral response in the presence of real world unpredictable external events. Imagine a cooperative group of MAS flying through an urban canyon searching for a particular truck. These vehicles presumably have the sensory capability necessary to detect, identify and track the truck as well as to avoid collision with buildings, signs, power lines and each other. Similarly, they presumably have sufficient aerodynamic agility to chase the truck, once it is identified, through the congested streets while maneuvering to avoid collisions and to coordinate their efforts. And these sensory response capabilities are robust to the high uncertainties associated with urban canyons: wide variations in

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ambient luminance; surface textures varying from concrete to painted or reflective surfaces; as complex an acoustic environment as may be imagined; wind gusts that may exceed the vehicle flight speed; etc.[9]

The concluding sections of this paper suggest that the behavior of autonomous mobile systems involves variation and flexibility in response that is significantly different from that of manmade automatic control systems, whether adaptive or not. And the basis for this point of view begins with the observation that the capabilities required for this urban canyon MAS scenario are 'life-like', in the sense of that imagined by writers of the movies mentioned above.

III. Agility and Autonomy in Biological Flight

Although the notion of automatic operation was a rare feature of human technology until the last century, and the notion of autonomy as described in the previous section is essentially absent from current human engineered mobile systems, autonomy is an inherent feature of biological systems response at all size and temporal scales. Somewhat surprisingly, this is an unappreciated fact given the incredible diversity of life processes and life forms on the Earth. In order to see this, the response of manmade automatic control systems needs to be contrasted with that of biological processes.

Return to the example of a tactical air intercept missile once again. The missile autopilot is designed to reject disturbances and produce airframe acceleration response to guidance commands over a range of altitude and velocity conditions that comprise the operational envelope for the missile. Within limits imposed by the autopilot design or control surface effectiveness, the autopilot will track whatever commands the guidance law generates and do so with a certain error and latency. Analogously, think of using the cruise control to modulate speed to accommodate the flow of traffic on an interstate highway. At first glance, this would seem to be similar to the response associated with a Peregrine falcon steady flight, perhaps with other hawks, during a seasonal migration.

The missile guidance system, itself an outer-loop feedback control system for the closed-loop autopilot controlled airframe dynamics, estimates the relative motion of the target with respect to the missile and generates acceleration commands to maintain an intercept course with the target. As the target maneuvers, the acceleration commands to the autopilot are automatically adjusted so that the missile maneuvers to accommodate target motion. As long as the acceleration commands do not exceed the autopilot magnitude limits, and the guidance system bandwidth is sufficiently low with respect to the autopilot/airframe bandwidth, the autopilot will track the commands and the missile will intercept the target within a certain margin of error. Further, the missile guidance system can be expected to have been designed in such a way that it will try to maintain an intercept course to the target in spite of target attempts to flee or to deceive the missile guidance system. Again, this would seem to be very similar to a Peregrine falcon's predation attempts on a fleeing duck or grouse.

The predicted performance of a tactical air intercept missile is often characterized by mean and standard deviation of the distance of closest approach in Monte Carlo simulation analysis. Reasonable random and bias errors, various target maneuvers, and various engagement initial conditions are introduced into a high fidelity dynamics simulation of the intercept scenario to account for the dominant uncertainties inherent real world scenarios. The missile system designer tries to adjust the various design parameters at his/her disposal to minimize expected miss distance (in the sense of mean and variance as measured through the Monte Carlo analysis) over all expected engagement conditions. Over the lifespan of the missile type, the design may be further refined based on analysis of flight tests or real world engagements. In any event, the design objective can be summed up as producing a *desired nominal behavior* characterized by minimized mean and variance of miss distance (or other suitable figure of merit). Further, the design analysis may establish confidence intervals associated with the nominal behavior, a measure of system robustness. While the details may differ greatly among other human engineered mobile automatic control systems, the design objective of *desired nominal behavior* over some range of conditions (i.e., robust) seems to be nearly universal.

A perusal of the animal behavior literature at first seems very familiar in the context of the discussion of the preceding paragraphs. Biologists make observations of animal responses, whether to artificial stimuli in a laboratory experiment or to natural stimuli in the field, characterize the responses using metrics such as mean and standard deviation, and establish confidence intervals using various statistical tests. Especially within many biology experimental laboratories, there seems to be an almost engineering mindset to describe *nominal behavior* and characterize variations with respect to the nominal. This is only good science! Experiments are carefully designed to be replicated a sufficient number of times so that statistical analysis of the results will be valid, allowing readers of the published results to infer the relative merits of the conclusions. Plots of response often include error statistics that may suggest, especially to the non-biologist, an almost engineered *nominal response*. This seems to be true whether the experiments involve study of behavioral conspecific interactions among animals; study of the neurobiology of animal sensory systems; reconstruction of flight mechanics and aerodynamics of animals flying in

wind tunnels; response of physiological processes to perturbations; study of biochemistry associated with metabolic processes; study of cellular mass and energy transport mechanisms; or study of protein transcription or nucleic acid replication.

The complexity of biological system responses at all scales requires this kind of approach. In order for an experiment or study to be capable of being replicated, which is an obvious requirement of a credible scientific endeavor, experimental conditions must be controlled, or the observational study scope narrowly defined, so that response and stimuli may be reliably correlated. While this is true with the study of any complex phenomenon, it seems to be inherent in essentially every biological study.

Unfortunately, and this is speculation, it seems that these tendencies to *nominal behaviors* exist primarily over conditions associated with the specific study. An impression one gathers from discussions with biologists or from the published literature, is that variation in response among different individuals within the same species, or even among subsequent trials with the same individual test subject, is large. Furthermore, this response variation may be correlated with very subtle differences among conditions in subsequent experimental setups; differences that would seem to be irrelevant in the context of the study.

This inference arises almost immediately from reading studies of animal social behavior. In vertebrate observational studies, behavioral differences among individuals in a social group often allow researchers to distinguish individuals at a glance. Read Jane Goodall's accounts of the Gombe Reserve chimpanzees or George Schaller's studies of lion prides on the Serengeti.[10,11] But this also seems to hold to a significant degree for fish schools, passerine bird flocks, bat colonies, in fact for any vertebrate group you can think of. Not only do animals assume different roles within structured social groups, but the behaviors of different animals playing the same roles differ in significant ways. The layperson impression of homogeneity in response for these organisms may only be due to limited resolution of the observation (e.g., sheep, and their shepherds, recognize other sheep!).

Animals typically associated with more stereotyped behavior also seem to exhibit large individual variations in response. It has long been known that honeybees change behavioral roles within a colony as they age. Stress, variations in food supply, weather conditions and other external conditions can modify the timing of these maturation effects. And as with vertebrates, honeybees show individual behavioral differences even within the same age class. Again, discussion with insect biology experimentalists leaves one with the impression that insect behavior is far from being predictable to the degree that one associates with mechanical systems.

IV. Implications for Manmade Autonomous Systems

To set the stage for the closing discussion, consider the following behavioral study thought experiment. Choose at random 100 missiles of a given model and fire them one at a time against targets of a given type under a range of reasonable engagement conditions. Chances are very good that the distributions of miss distances, times to intercept, trajectories, etc., would be consistent with, though not identical to those obtained from a Monte Carlo simulation study of the same missile model evaluated over a similar range of scenarios. That this is a reasonable expectation emerges from two related phenomena: the dynamics models in the simulation have been refined to yield a high fidelity representation of the actual scenarios; and the missiles have been designed to yield consistent, reproducible *desired nominal behavior*. This kind of predictable behavior is often termed 'mechanistic', even when ascribed to human behavior such as that of a dance troop choreographed rehearsal.

Now perform an analogous experiment with a falconer releasing 100 trained Peregrine falcons of similar age and training experience one at a time against a sequence of fleeing grouse (recall it is a thought experiment). On any given day, the flight performance of a trained bird-of-prey such as a falcon may be influenced by many factors including how recently it has eaten, its molt condition, the season, its general state of health, etc. Although these are trained animals, one would not be surprised to find the performance variation to be quite large. That is, the spreads in the distributions of number of passes to capture, times to capture, paths flown during the pursuit, etc. would be large when compared with related figures of merit in the missile experiment. We expect this since animals, after all, are animals and their behavior is rarely 'mechanistic' in the sense of being highly predictable over long time scales.

Finally perform a similar experiment with release of 100 wild, untrained Peregrine falcons, again of similar ages, one at a time against a sequence of fleeing grouse. We naturally expect the performance variation to be even larger than with the trained animals. The object of the training, after all, is to produce repeatable, predictable *desired nominal behavior*.

What does this have to do with design of agile MAS? Even if these observations with respect to biological autonomous response are valid as speculated, correlation of response flexibility with biological autonomy does not imply causation. Biological systems emerging through the interplay of the complex processes of evolution may exhibit response variation as a byproduct of the variations necessary for powering evolution. Certainly, species with highly specialized behavior are more seriously affected by environmental change than those with more varied

behavioral repertoires. Most of the animal extinctions of the past few centuries involve such ecological or behavioral specialists. Hence animals capable of tolerating large ecological perturbations would naturally be supposed to have behavioral repertoires, individually and/or collectively, that allow adaptation to the environmental fluctuations.

Although correlation certainly does not imply causation, an argument can be developed that suggests behavioral response flexibility is, in fact, naturally and intrinsically associated with autonomous behavior. Further, that MAS capable of interacting with their surroundings in the complex ways envisioned by technologists will, at the very least, exhibit the variations in response associated with highly trained animals (or human groups!) and will not exhibit the relative high performance predictability currently associated with automated machines. Anyone who has walked a normally well behaved male dog in the vicinity of a female dog in season will appreciate the difference.

An outline of such an argument might begin with the definition of *an autonomous system as one that exhibits context-appropriate behavioral responses to essentially unpredictable events*. One might then make the following assertions, each of which is disprovable, at least in principle:

- Real world complex environments, whether natural or manmade, generate unpredictable events over behaviorally relevant time and spatial scales
- It is impossible to model the important dynamics real world complex environments, whether natural or manmade, at sufficient levels of fidelity required to *a priori* define context-appropriate responses
- The degree of flexibility associated with a behavioral repertoire, independent of the size of a behavioral repertoire, determines the range of context-appropriate responses available
- The range of context-appropriate responses available determines the range of unpredictable events that can be accommodated

A reasonable inference from these assertions is that environmental complexity drives a requirement for behavioral response flexibility and makes it a necessary attribute for any system capable of accommodating uncertainties associated with a real world complex environment. This, of course, falls far short of a proof that behavioral response flexibility is necessarily associated with autonomous systems, but it motivates consideration of the possibility that such might be the case. The possibility merits further investigation.

If the preceding discussion has merit, the natural question emerges of whether human society is prepared to accept that potentially or intentionally lethal MAS may operate more like trained animals than more familiar automated mechanical devices. We are reasonably comfortable with the knowledge that even highly domesticated animals occasionally exhibit undesirable behavior. Whether we can become comfortable with the potential for similar behavior from MAS will be an open question until such systems arrive.

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Appendix B

Flight Controls and Performance Challenges for MAVs in Complex Environments

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Successful flight control of agile, autonomous Micro Air Vehicles is a distinct challenge from controls of any manmade flight vehicle. Efficient, controlled, highly maneuverable flight of MAVs – in summary, flight agility - is challenging enough in quiescent environments. Adding the effects of atmospheric disturbances and obstacle avoidance produces an almost daunting task, whose resolution has led to interest in bio-inspired approaches, and has raised basic questions in how to possibly abstract features from flyers in nature to improve manmade flight vehicles. Classical subjects such as vortex shedding and membrane deflections need to be revisited in a new, multidisciplinary and highly nonlinear context. We explore several themes in MAV aeroelasticity, bio-inspired flight controls and unsteady aerodynamics. Examples include the role of flexible airframes in potentially attenuating response to gusts, how large-amplitude-large-frequency prescribed motions can be useful for gust-response studies in ground test, and some advances in indoor flight test of MAVs and in hover test-stand tests of flapping-wing fluid-structure interaction.

Introduction

Micro/Nano Air Vehicles (MAVs/NAVs) are the most maneuverable man-made flight vehicles, and also potentially the most sensitive to disturbances in complex flight environments. Compared to the merely "small" UAVs or conventional radio-controlled hobby-type airplanes, the extremely small size, light weight and slow flight speed of MAVs creates profound complications in aerodynamic efficiency and agility. But these very same factors suggest important advantages ripe for exploitation. Operation in an environment of gust and crosswind spatial frequency content on the order of their wingspan, and of gust speeds comparable to the vehicle's top flight speed, can condemn a conventionally-engineered airplane to erratic, poorly controlled flight. Avoidance of obstacles may be problematic, if not outright impossible – not only because of gusts, but because of ground-effect and related flowfield phenomena when flying in the vicinity of walls. Low wing loadings, which are necessary for aerodynamic efficiency and reasonable flight endurance, exacerbate the problem of gust response. But small moments of inertia and novel coupling of flowfield time scales with airplane system time scales can create new opportunities for actuation and maneuvering. This coupling can be with the rigid body dynamics, with effects of flexible structures (either aeroelastic or inertial), or with effects of vortex shedding and other flow-separation phenomena – and possibly all three.

The MAV flight mechanics challenge consists of generating sufficient control power to maneuver; to negotiate gusts while keeping sensors on target; to remain controllable in ground effect or in the presence of other obstacles; to precisely maintain path and orientation in confined spaces, and cluttered/complex environments; to "perch" and perform related maneuvers of precision landing; and to achieve all of these with minimal onboard energy storage, with low-

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resolution air data sensors and with limited onboard computational resources. Collectively the MAV flight mechanics challenges can be summed up as "agility". An alternative definition of MAV agility is the capacity to perform precise, high-rate aerial maneuvers.

Candidate strategies for achieving flight agility often involve recourse to biological inspiration, by considering the examples of birds, bats and insects. One has most likely witnessed a bird performing a complex flight maneuver in order to avoid an obstacle or fly in a gusty environment. Likewise, who has not witnessed a fly impact a glass window only to recover and attempt to fly through the glass many more times? Abstracting to considerations of aeronautical engineering, one example of desirable properties in natural flyers is exploitation of fluid and structural instabilities and nonlinearities to increase control power. Another is massively flexible structures, which deflect to absorb gust energy and which admit actuation at resonant frequency, thus reducing flight power requirements. Yet another is close coupling of control actions among attitude-control, position-control, flight stabilization and navigation. These approaches are intuitively most obvious for flapping-wing MAVs, but flapping configurations are also the most difficult to implement with engineering rigor, because the underlying fundamental physics remains poorly understood and is far from being captured in engineering-fidelity methods of analysis and design. And even for fixed-wing MAVs, abstractions of the flapping flight of animals are also useful for study of gust response and flight mechanics where wing flexibility is important. The question, then, is how to build the requisite understanding of flight physics, motivated by study of examples in nature, to design MAVs for flight agility.

Decades of research in unsteady aerodynamics can be projected onto the application of MAVs, with suitable extension to the heretofore largely academic problems of low Reynolds number, laminar/transitional flows at high reduced frequencies and amplitudes. We must assess the extent to which the MAV problem is an incremental extension to already described unsteady aerodynamics, or if existing approaches are even qualitatively inadequate.

Perhaps the most pressing question is the role of nonlinearities in the aerodynamics, the structural dynamics and the controls. Coupling between these three is crucial for successful engineering design of MAVs.

In this paper we consider five interrelated aspects of the MAV flight mechanics, control, and aerodynamics:

- A selection of recent results in low-Reynolds number high-rate airfoil pitch-plunge, as surrogate for study of gust response in the presence of massive flow separations, and for an example of maneuvering-flight in nature.
- Exploration of aerodynamic advantages of wing flexibility at the vehicle scale, and the effect of wing flexibility on the flight dynamics, by comparing simulation with flight test.
- Analysis of flexible-wing flapping-wing MAVs in hover, with eventual aim towards multidisciplinary engineering optimization.
- Flight control issues for autonomous MAVs, including effects of flexibility
- Outline of biologically-inspired concepts in MAVs, such as sensing modalities that could be abstracted from nature to improve MAV maneuverability and gust tolerance.

1. Experiments in High-Rate Unsteady Aerodynamics

Flapping-wing flight in nature[1,2,3,4], and attempts to abstract flapping for lift/thrust/flight control, are a fascinating problem in unsteady aerodynamics. The vastness of the subject gives pause even to critics who regard aerodynamics as a "mature" discipline. Attempts to model the effects of high angle of attack, of dynamic stall, of complex interactions between shed vorticity

and the time-history of aerodynamic loads have met with mixed-success at best[5]. The same can be said for efforts to abstract flapping-flight in nature to engineered applications – namely, MAVs. For example, what do animals do to avoid being bounced around by wind gusts, in circumstances where even highly-maneuverable radio-controlled airplanes are helpless? The solution can not lie merely in high thrust to weight ratio or large control derivatives. One research direction is to observe flight in nature, looking for subtleties in animals' sensors, actuation schemes and means of closing the control loop. Another is to revisit aspects of classical unsteady aerodynamics, already well established in applications ranging from wind turbines to flutter analysis, and to extend this work to the frequencies of motion and Reynolds numbers relevant to flying animals and to MAVs.

A series of recent papers on nominally two-dimensional airfoil pitch-plunge experiments in the Air Force Research Lab's Horizontal Free-surface Water Tunnel (HFWT) and its "High-Intensity Pitch-Plunge Oscillator" (HIPPO) rig have been concerned with vorticity production vs. motion kinematics in two degrees of freedom[6,7,8]. Details of the HIPPO rig and its operation are given in Ol et al[7]. A brief schematic is shown in Figure 1. We attempted to build on the vast and disparate literature of airfoil dynamic stall[9], aquatic and aerial animal propulsion by flapping[10] and MAV flapping-wing applications[11] by considering high rate motions, nonsinusoidal motions, cases where pitch frequency and plunge frequency differ by integer multiples, and so forth. There is always the challenge of how to make rational abstractions from multi-DOF aeroelastic flapping of 3D wings to the limited but experimentally well-controlled environment of 2D rigid airfoils. Nor it is necessarily clear how lessons from this or that airfoil pitch-plunge case can be generalized to the design of practical MAVs. Indeed, perhaps the great challenge in MAV aerodynamics, flight mechanics and controls is how to project disciplined scientific enquiry onto the practical task of optimizing vehicle design. To be useful for MAV applications, study of rigid wings in water tunnels, while "clean" from the viewpoint of fundamental fluid mechanics, must be augmented by parallel work in other facilities and by observations in nature. Aspects of both of these considerations are given in later sections below. Presently we consider two somewhat new examples attempting to related pitch-plunge motions to MAV flight applications, and eventually to exploration of MAV flight agility. At present, in the abstract sense, we are more interested in the interaction between the flowfield response and the forced-motion of airfoils and wings. The next step will be to consider the relation between flowfield response and the vehicle flight mechanics.

The first example is the very important problem of MAV "perching", where the vehicle makes a precision landing in a confined situation, using high angle of attack force transients and forecasting the appropriate time-history of lift and thrust to enable the precision maneuver. The inspiration is from "flight testing"[12] of large birds (Steppe Eagles). Because particle image velocimetry of the flowfield about the bird's wing is a rather problematic venture, it would be convenient if an abstraction in the water tunnel could capture at least qualitatively the flowfield physics relevant to the perching maneuver.

The second example considers how a flapping wing may behave in a gust, with the "gust" modeled by a perturbation in the airfoil motion superimposed on the "flapping" (that is, on the pitch-plunge). Here again, flowfield velocimetry for flight test of gust response is unlikely, and it is very difficult to obtain even a measurement of force on the flight-article with time-synchronization of measurement of the gust profile. The tentative solution is again to pursue a very simplified model in the water tunnel, taking advantage of the water tunnel's low physical speed of events for a given dimensionless reduced frequency, while matching Reynolds number to flight-relevant values for MAVs and birds.
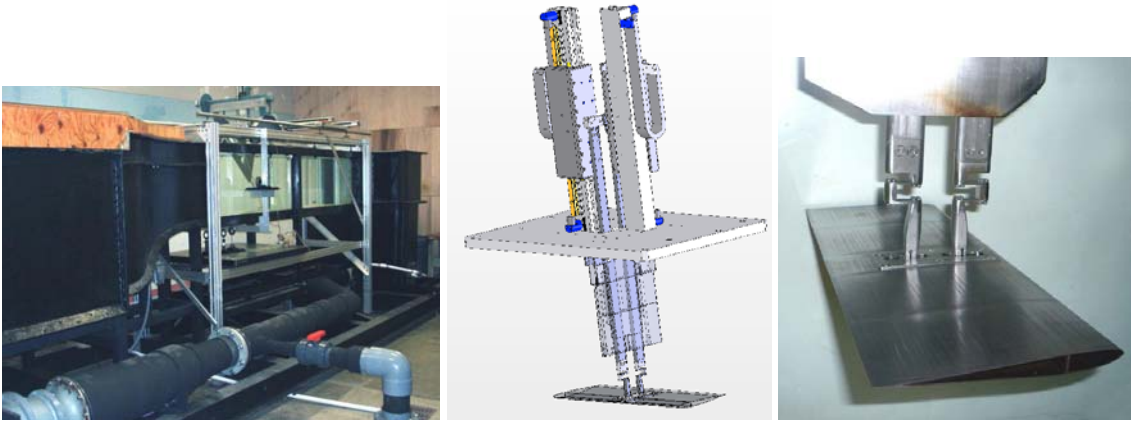
Figure 1. AFRL Horizontal Free-surface Water Tunnel (left); schematic of pitch/plunge rig and airfoil model (middle); and SD7003 airfoil installed in HFWT test section, with plunge rods in position prior to a run (right).

Eagle Perching Maneuver

Based on flight observation[13], the Steppe Eagle perching maneuver (Figure 2) can be roughly approximated as follows:

- begin from steady-level cruise at 8 m/s, with wing at nominal $\alpha = 10°$
- decelerate steadily to zero velocity, over a distance of 2m measured along the ground
- while decelerating, perform constant-rate pitch-up about the wing quarter-chord, such that upon coming to rest in the "perched" position, $\alpha \sim 60°\text{-}70°$ is attained.

Figure 2. Steppe Eagle in deep-stall stage of perching maneuver[12]

We ignore the change in vertical position of the bird, assume a rigid spanwise-uniform wing that pivots at constant rate, and assume constant deceleration in forward flight speed. This gives a pitch rate of 120°/s, and linear deceleration of 16 m/s^2. A dimensionless pitch rate assumes a constant forward speed and is not literally meaningful for a true perch maneuver. However, we shall take the mean forward speed (4 m/s), which gives K = 0.08. Assuming 25cm mean aerodynamic chord for the Steppe Eagle, Re ~ 60K.

HIPPO can support α = 45º maximum, and the HFWT only accommodates a constant free-stream velocity. Subject to these limitations, a K = 0.08 linear pitch ramp-and-hold is straightforward to implement, and this should qualitatively represent the flowfield associated with the perch of the eagle, at least for those conditions where the eagle's wing does not undergo large spanwise variations such as feather deployment, spanwise twist, or change of span or sweep. Snapshots of the motion, with dye injection at the airfoil leading edge, are shown in Figure 3.
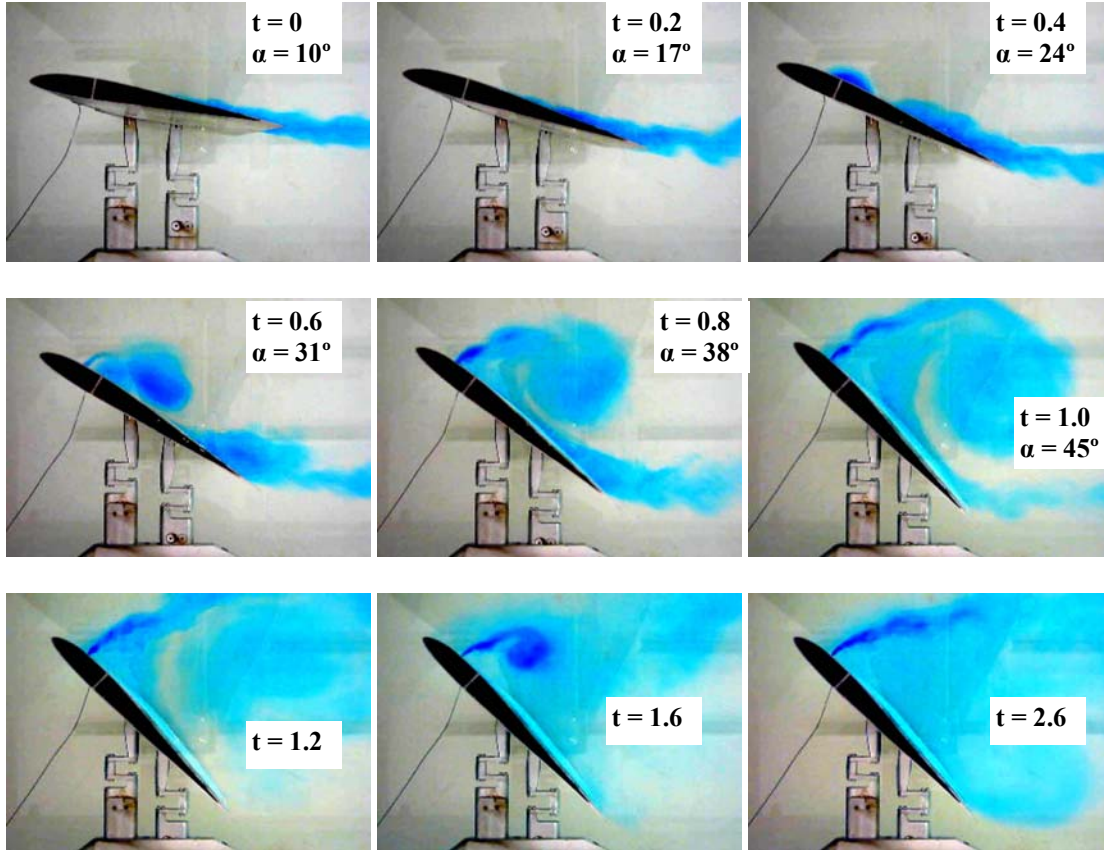
Figure 3. "Eagle perching maneuver" (linear pitch-up); nine phases of motion, dye injection at airfoil leading edge, Re = 60K.

A leading-edge vortex begins formation at α ~ 24º, and is prominent by α ~ 30º. The LEV keeps growing for the duration of the motion (α = 45º) but is shed when the motion stops. By this time, of course, the eagle will have come to rest. But if we follow the flowfield evolution further, eventually the motion-induced LEV will shed, and will be replaced by a Karman vortex street, with vortex shedding alternatively from the airfoil leading and trailing edges. Clearly a steady-state α = 45º is not an efficient way to produce aerodynamic force, nor a stable way to fly, because of the vortex shedding. But the pitch-up associated with perching is shown even this highly simplified experiment as a viable way to produce a transient in lift and to bleed off flight speed. It remains to measure, of course, the integrated aerodynamic loads, and to assess the phase relationship between motion kinematics, flowfield evolution and aerodynamic load time-dependency. Indeed, this is the principal problem of MAV unsteady aerodynamics and flight mechanics.

Perhaps the most troublesome discrepancy between the abstracted flow in the HFWT and the actual perching maneuver of the eagle is the latter's change in forward velocity during the maneuver, terminating in a full stop. This raises the broader issue of how to unify analysis of forward-flight and hover. In hover, how does one define Reynolds number, reduced frequency

and so forth? In most treatments (for instance, Shyy et al[4].), in hover these dynamic parameters become merely kinematic, since there is no longer a flow time scale, and one resorts to a degenerate time scale defined by the flapping speed and chord or stroke length. One possible resolution is to revisit momentum theory, replacing the flapping-wing as an actuator disk[14] and taking the mean downwash velocity (for positive thrust) as the characteristic flow speed.

We can not, at present, conclusively say that this sort of flowfield "captures" the relevant situation for the eagle during the perch maneuver, in the absence of at the very least a set of detailed force measurements on both the bird and the airfoil model. However, knowledge of the flow separation time history as measured in the HFWT is useful at least in understanding why, say, the bird would deploy leading edge high-lift devices at a particular time throughout the perch maneuver, and how similar functionality could be designed for bio-inspired designs.

Response to Vertical Pseudo-Gust

Gust simulation in wind tunnels is an intriguing attempt to study MAV flight dynamics while retaining the convenience of a model-fixed frame and the diagnostics suite available in ground test. While gust-tunnels are more commonly associated with airplane aeroelastic testing, a number of low-speed wind tunnels suitable for MAV-scale experiments are fitted with mechanisms to introduce large-amplitude variations in free-stream conditions, with sharp on-demand onset and termination of the flow perturbation, without significant deleterious effects on flow quality. A typical example of a tunnel gust-generation mechanism is shutters downstream of the test section (for example, the Illinois Institute of Technology Wind Tunnel[15]). Shutters can operate much faster than an attempt to throttle the tunnel drive system, and are thus well-suited to producing streamwise-component gusts. In water tunnels this may also be possible, but with the danger of water-hammer; overpressure would scale as $\rho a \Delta U_\infty$, where ρ and a are the density and speed of sound in water, respectively. In a free-surface water tunnel such as the HFWT, a shutter system would just cause spillage out of the test section, and is therefore not workable.

Vertical gusts or crossflow gusts are perhaps more dangerous for MAV applications than streamwise gusts, but are also harder to model in tunnels, at least if preservation of good flow quality is important. The alternative, which is mathematically not equivalent to a true gust and will therefore be called here a "pseudogust", is to subject the model to a controlled, violent descent or ascent maneuver (that is, a plunge) while the tunnel free-stream remains constant. This is the approach taken here, with airfoil experiments in the HFWT. The pseudogust in the vertical direction is taken to have top-hat profile in time, duration of one convective time, and amplitude equal to the free-stream velocity (thus, plunge-induced α = 45º in the quasi-steady sense). It is realized through a linear-ramp in airfoil plunge, and is superimposed on a sinusoidal pitch-plunge, which is an abstraction of quiescent flapping flight. The pitch-plunge parameters are: reduced frequency k = πfc/U_∞ = 2, plunge amplitude 0.1c, pitch amplitude 13º with mean-offset +4 º , pitch leading plunge by the often-used 90 º phase. The pitch-plunge starts from rest, runs for 2.25 periods, then the gust commences, continues for ~0.64 periods (that is, one convective time), ends abruptly, and the gust-free pitch-plunge continues for another ~3.5 periods before abruptly coming to rest. The rationale for running this number of pitch-plunge periods is evidence from prior work on moderate-amplitude pitch and plunge[6] that flowfield periodicity is achieved after some 2 periods after pitch-plunge motion commencement. The segment from t/T = 1.5 through 4.0 is given in Figure 4, with the gust-induced angle of attack (due to plunge) shown in the green curve. Following quasi-steady concepts, the pitch and plunge contributions could be superimposed to a "combined" angle of attack, but such an approach is probably inappropriate for such high motion rates and amplitudes. Pitch rate effects, in the quasi-steady sense or in the sense of the Theodorsen formula for lift coefficient[16], are removed by the choice of pitch pivot point at x/c = 0.75.
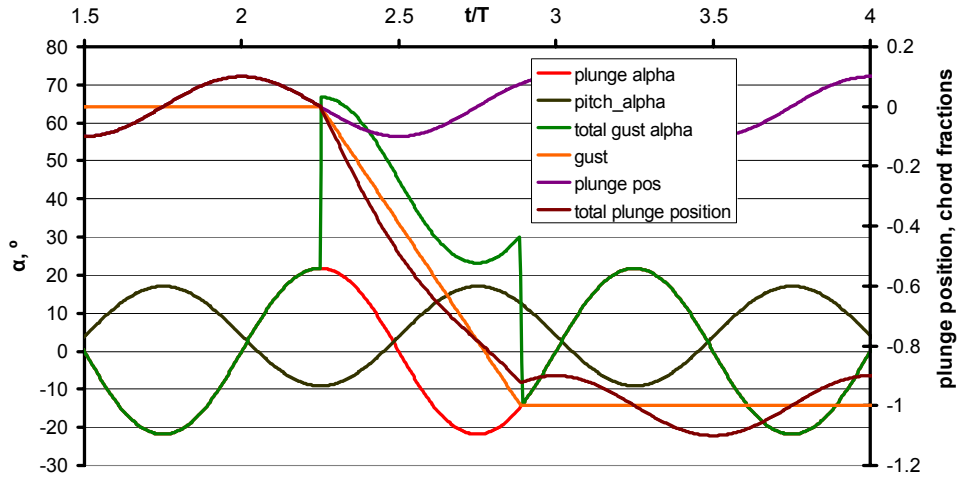
Figure 4. Sinusoidal pitch-plunge and gust profile for "pseudogust".

Dye injection results for every half-period (at which the geometric incidence angle is just the offset value, α = 4°) are given in Figure 5. Other than for what might be termed diffusion, the dye streak for t/T = 2.0 differs little from that for t/T = 1.0. The "gust" begins at t/T = 2.25, whence at t/T = 2.5 a vortex pair over the airfoil suction side is discernable. The pair consists of a LEV and its companion just upstream of the trailing edge. In the near-wake, another vortex is visible. This is a manifestation of the effect of the "gust" on the wake itself. Kinematically the gust is completed before t/T = 3.0, but its residual effect – a large, diffuse vortex blanketing the airfoil suction side – is quite prominent. A further 2 periods of pitch-plunge oscillation is required for this effect to convect far enough into the wake such the remaining flow reverts to periodicity. Periodicity is evinced by the fact that at t/T = 5.5 the flow differs little from the snapshot at t/T = 6.5, for example.
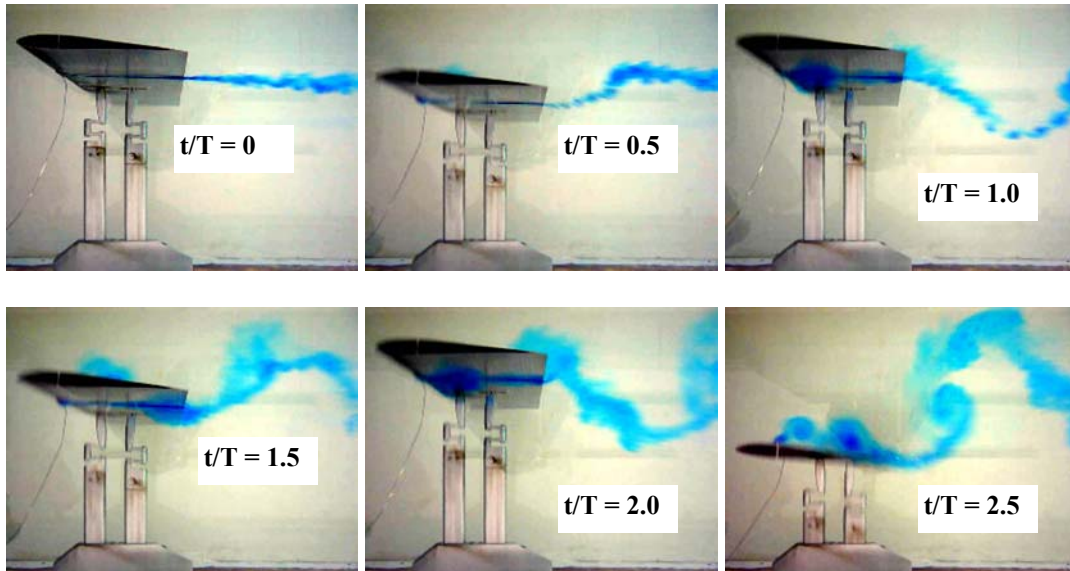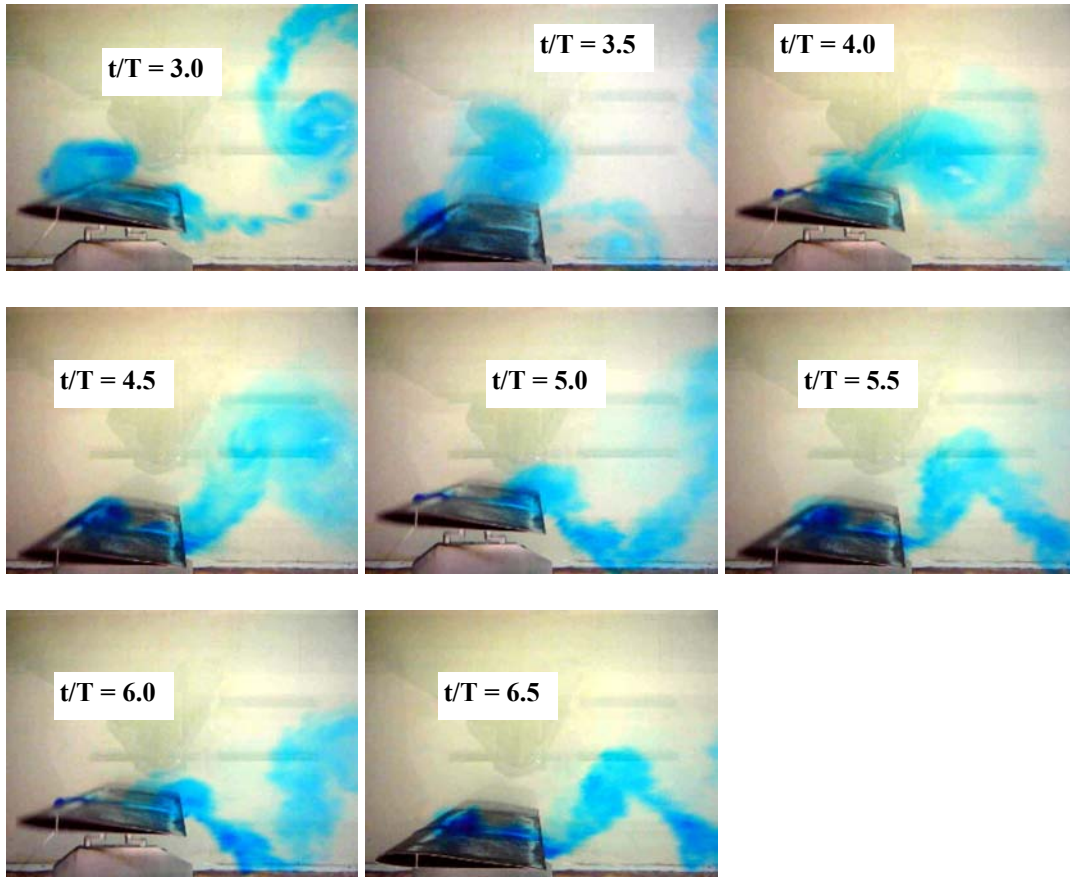
Figure 5. Ramp-plunge "pseudogust" superimposed on sinusoidal pitch-plunge

One can speak of the transients associated with the gust either in terms of the convective time, $t^* = c/U_\infty$, or by the period of oscillation, t/T. The ratio of t^* to the period of oscillation depends only on the reduced frequency of oscillation, $k = \pi fc/U_\infty$. In Figure 5, the two periods of oscillation required to attenuate the gust's effects are roughly $3t^*$. For further analysis of flapping-wing MAVs and comparison between fixed-wing and flapping-wing, the gust attenuation time should be compared to the flow response time of deflecting a conventional aileron. That is, one is interested in comparing how rapidly the flow responds to a control effector, and thence how rapidly the airplane responds to the flow.

2. Role of structural flexibility in MAV flight dynamics

From the viewpoint of structural design in aerospace engineering, flexibility has often been viewed as a negative trait, and the importance of design for rigid-wings has resulted in heavier, stiffer wing structures. But the wings of most flyers in nature are known to flex significantly[4].

Structural flexibility introduces both complications and opportunities for MAV flight mechanics and control. Here by "flexibility" we mean designed structural compliance and local shape-change, of which a prototypical inspiration is a bird's feathers deflecting to allow the bird to reject a gust or to fly at high angles of attack. This is distinct from "morphing", which is large-scale shape change such as the bird folding its wing to enter into a dive.

Pilots of radio-controlled MAVs report that MAVs with a "flexible" wing (i.e., covered in a latex material) are easier to fly than MAVs with a rigid wing[17]. We reason that for a MAV with a flexible wing, gust energy would to some extent be absorbed by the flexibility of the structure. This absorption and subsequent dissipation of the energy would reduce the amount of energy going into moving the vehicle, thereby reducing the impact of the gust. Additionally, Breuer, et al.[18] and Gursul et al.[19], have shown that airfoils which are compliant delay stall and reduce the separation region.

The impact of a flexible airframe on the response to disturbances was studied by Stewart et al.[20], who showed that the airframe exhibited different responses to controlled input disturbances (Figure 6, left) and that the rate- and positional oscillation damped more quickly for the case of a flexible wing (Figure 6, right). These results support the observation that MAVs with a degree of flexibility are less susceptible to disturbances. So the questions that need to be addressed are (among others):

1. To what extend does vehicle flexibility violate the assumption of a rigid body airframe?
2. Can flexibility effects be added to the dynamic equations of flight and, if so, will it improve autonomous flight control?
3. Can sensors be added to the airframe to measure flexibility such that this information can be used by the flight control system?
4. Can the flexibility be modified during flight so as to change the flight performance?
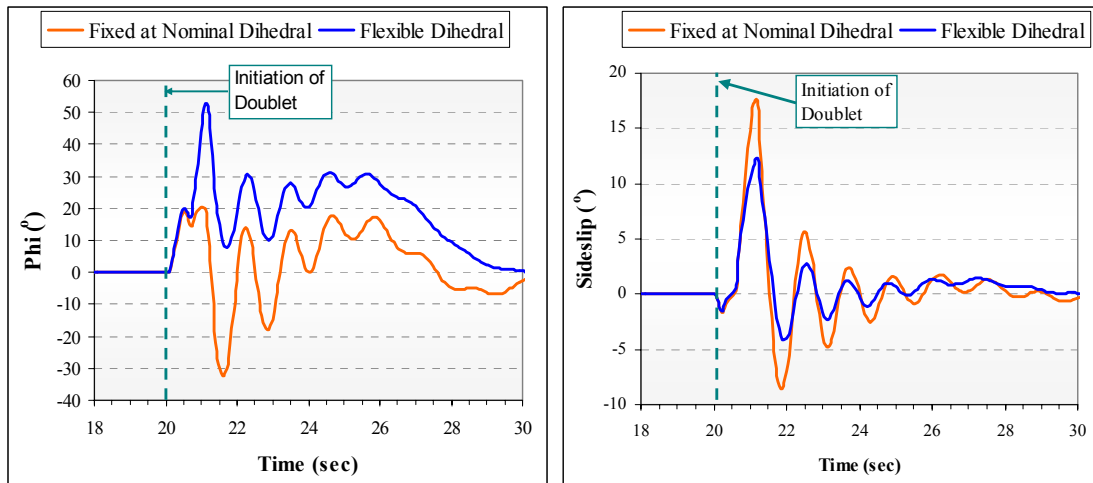
Figure 6. Roll angle response (left) and sideslip variation (right) vs. time resulting from a pitch doublet for a fixed and flexible MAV configuration

The answer the first question above was addressed by Stewart[20]. The flight dynamic equations of motion (e.g., Etkin[21]) assume a rigid body and time-invariant inertia tensor. Flexibility's effect on the airframe mass properties and on the aerodynamic coefficients and stability derivatives were modeled. Clearly, an effect is present but to what extent this effect impacts the autonomous control is yet to be determined.

To further understand the effects of this flexibility and to assess the validity of the model incorporated by Stewart[20], flight hardware was made to gather experimental data[22]. Here, the GENMAV[23] model was used as a baseline configuration and hinges were added to the wing root

and were attached with a spring-damper system. The model is shown in Figure 7. It is planned that future testing with this model will help validate the simulation developed for a "flexible" wing MAV so that future studies can focus on addressing the second question presented above.
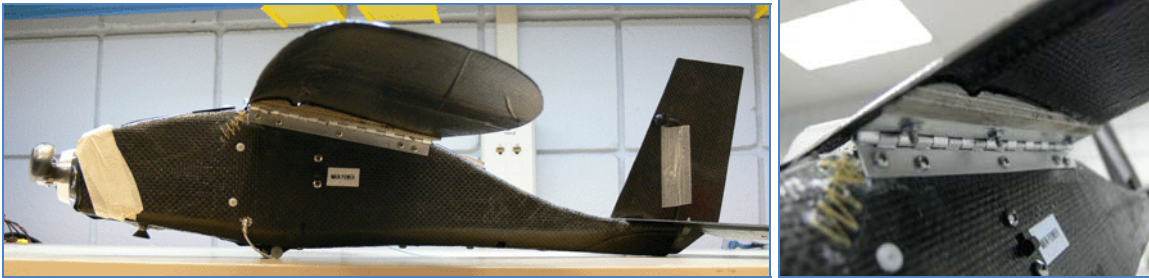
Figure 7. GENMAV vehicle outfitted with hinged wings[22]

A complimentary effort by Costello is also underway[24], with the goal of developing an articulated/segmented wing model that can be used to model the effects of wing flexibility. This is illustrated in Figure 8. Here, a first approximation is assumed as a spring-damper joint at the wing root. The model development by Costello will allow for a 1-to-*n* spring-damper segments of the wing spar to represent flexibility. With such a model in place, the wing can be "tuned" for the optimal amount of flexibility for a given flight-mechanics objective. The model will also allow for enhanced autopilot development, where information about the deformation can be included in the control system. This addresses the third question posed above.

**Figure 8. Articulated wing approximation**

Taking this concept to the next level, one can address the fourth question above, by asking, for example, whether the spring-damper structure could be stiffened or relaxed in-flight to allow for aggressive flight maneuvers. This concept is closely related to the way some natural flyers operate.

3. Flexible-wing flapping-wing MAVs in hover

Structural flexibility has potential benefits not only for flight mechanics in cruise, maneuver and gust rejection, but also in hover and in particular for flapping-wing MAVs. To the extent that MAVs can benefit from bio-inspiration, we anticipate that aeroelastic tailoring can be used to improve the performance of flapping wing MAVs relative to designs with rigid structure. Tailoring of the wings to twist along the span when loaded can lead to gust alleviation and improved lift distribution along the wingspan[25,26]. Flexible wings can be designed for variable or reversible camber depending on whether they are in an upstroke or a downstroke, much like wings of an insect or hummingbird[27,28]. Flexibility can allow degrees of freedom in rotation, bending and twist, beyond directly-actuated degrees of freedom, thereby reducing the actuation requirements[29,30,31]. Flexible wings operating at resonance can cause increase in flapping amplitude for a given power input, thereby increasing the propulsive efficiency.[32,33,34] With a

flexible structure, the energy otherwise expended to slow and stop the wings when reversing direction during flapping can go into bending the structure, which is then released like a spring, aiding in accelerating the wing in the opposite direction. This elastic storage of energy decreases the total power-required.[35] Together, these potential advantages of flexibility can improve the efficiency and agility of flapping-wing MAVs.

Any systematic attempt to investigate the vast space of parameters associable with flapping-wing geometry, kinematics and structure must be predicated on moderate-fidelity methods with minimal computational cost, enabling fast iteration. But the salient physics needs to be retained. A computational framework should include handling of unconventional and potentially complex structural layouts, time-dependent responses of structure and flowfield with selectable fidelity of representation of nonlinearities, and should maintain reasonable accuracy for both attached and massively-separated flows. The framework should be able to explore parameter sensitivities per defined performance metrics, and should be amenable to wrapping in an optimizer. Our preliminary effort begins with modeling the kinematics of hovering flapping-wing flight, including a quasi-steady blade element aerodynamics model, a linear beam finite-element model, a spectral element method for capturing system dynamics, a gradient-based optimization tool, and an adjoint method for computing sensitivities of design objective functions with respect to design variables. This was used for initial studies of how structural flexibility, wing kinematics, and wing planform affect forces produced by the wings, along with the power required[36]. In the next iteration, we are integrating a commercial nonlinear finite element model and a hierarchy of aerodynamics models from vortex panel methods to Navier-Stokes CFD.
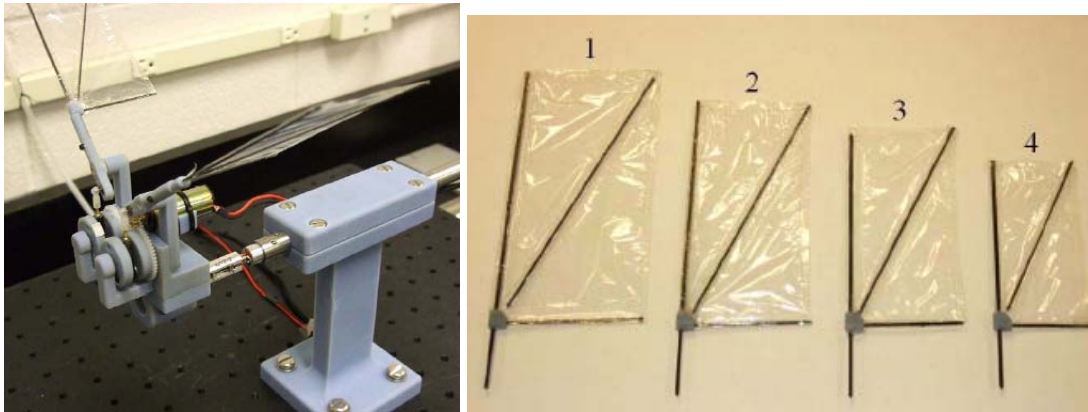
Figure 9. Flapping Mechanism Mounted on Force Balance (left),[37] and typical wings installed on flapping rig (right)

While computational methods are useful for optimization and engineering design, experiment not only validates computations, but is useful for organic discovery. Our flapping-wing experimental facilities include a hover bench-test rig and an indoor flight test environment.

The bench-test rig is a simple one degree of freedom flapping mechanism mounted on an air-bearing table to measure thrust,[37] and 6-component force balance for measurement of dynamic loads (Figure 9). Wings were constructed from carbon fiber rods for spars and Mylar for the membrane. Initial testing was with four different wings (Table 1 and Figure 9), with a flapping frequency-sweep to quantify the role of wing planform area.

Wing	Weight (g)	Spar Length	Chord Length	Wing Span
1	0.89	4"	2"	12.1"
2	0.79	3.5"	1.75"	11.1"
3	0.73	3"	1.5"	10.1"
4	0.59	2.5"	1.25"	9.1"

Table 1. Wing Properties for benchtop hover rig[37]

A figure of merit was used to analyze the overall performance: $Figure\_of\_Merit = \dfrac{C_t^{3/2}}{\sqrt{2}C_P}$

where C_t = coefficient of thrust and C_P = coefficient of power. Figure 10 shows Figure of Merit vs. Thrust for the four different wings.[37]
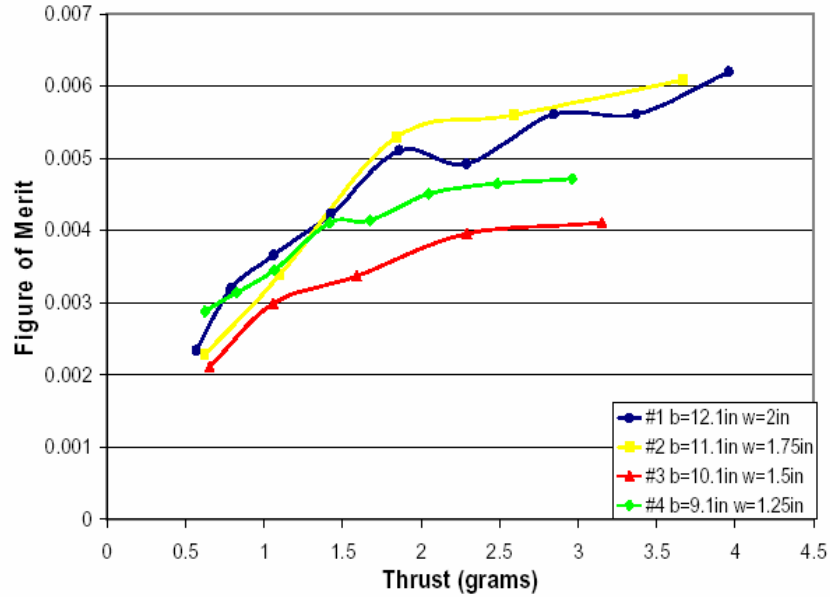

Figure 10. Figure of Merit vs. Thrust for Different-Size Wings[37]

Varying the stiffness of the wings also affected the figure of merit (Figure 11). This difference is due to the larger deformations present in the more flexible wing (Figure 12).[37]
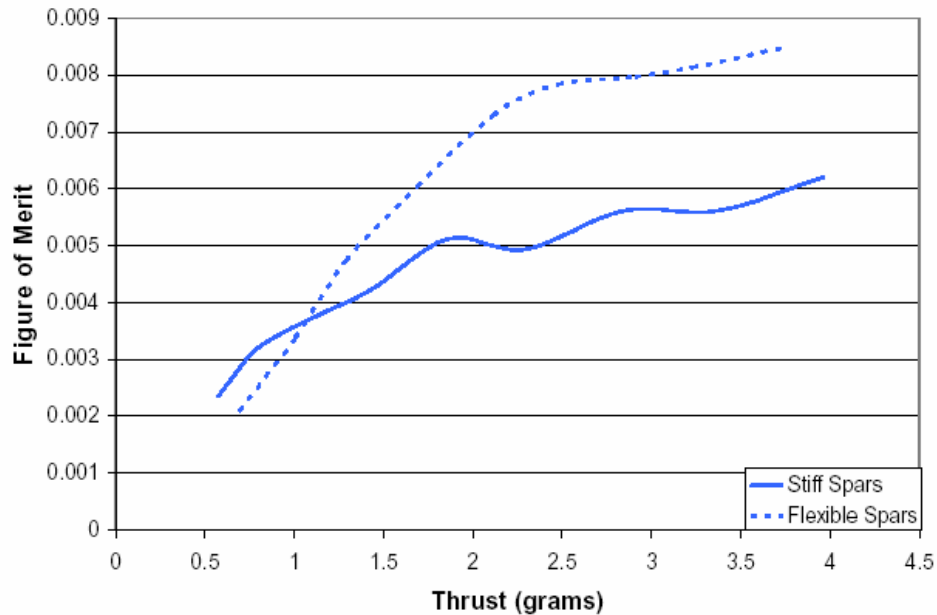
Figure 11. Figure of Merit vs. Thrust for Different Spar Stiffness[37]
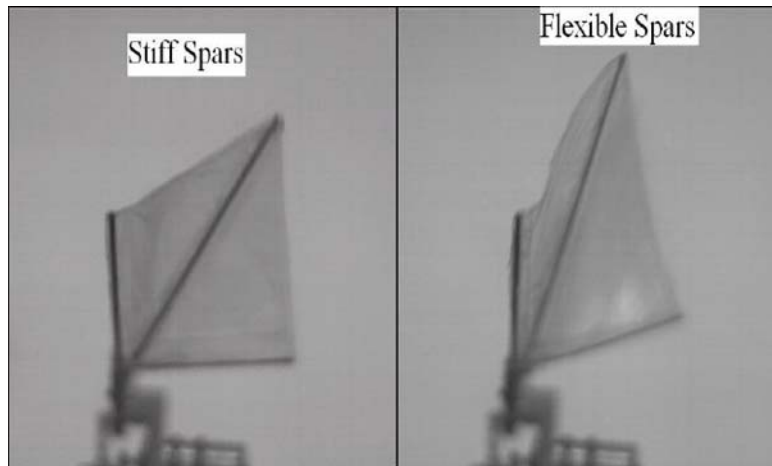
Figure 12. Wing deformation (stiff spar and flexible spar) from high-speed camera images[37]

Capabilities to be added to the flapping-wing bench test system include generalization of the actuation kinematics to three degrees of freedom (flapping, wing rotation, and fore-aft sweeping motions), and a high-speed visual image correlation system. This system has been successfully used to measure the position and deformations of a flapping wing by the University of Florida[38,39]. Comparison of loads in ambient air vs. in a vacuum should give insight into the distinction between aeroelastic vs. inertial deflection of the flexible wings.

The flight-test facility at Wright-Patterson AFB consists of a 28'x28' room with a ceiling height of 50' (Figure 13), fitted with a VICON motion tracking system[40] with 36 cameras. This system tracks multiple vehicles with sub-millimeter accuracy. The facility is similar to the MIT Real-time indoor Autonomous Vehicle test ENvironment (RAVEN).[41] Position and attitude data from the VICON system is sent to a real-time computer which determines control inputs and sends signals through the vehicle remote control transmitter, allowing for autonomous control without any sensors onboard the vehicle. Position tracking can be used for study of MAV flight mechanics and system identification, by comparing control inputs with the resulting history of vehicle position and attitude, and their derivatives. Alternatively, this facility will also allow for the development of new onboard sensor technologies while providing an accurate truth source. In future iterations we plan to introduce a means of controlled gusts.
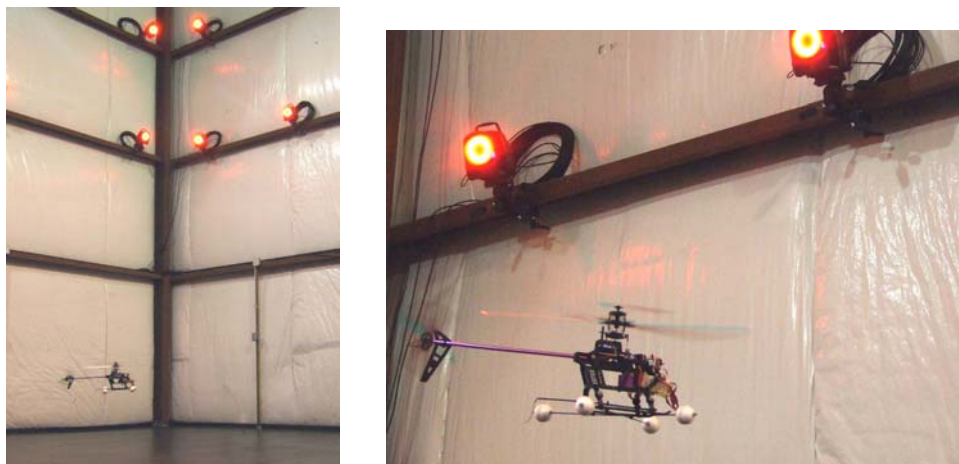
Figure 13. Indoor flight test facility, with portion of VICON camera suite shown.

4. Flight control for autonomous agile MAVs

The usefulness of MAVs is doubtless far greater as autonomous platforms, especially in swarms, than as radio-control airplanes. Flight agility is only marginally useful if constrained by the abilities of a human operator, even in the unlikely case that man-machine interface is stable and always available. Autonomy in engineered systems typically implies that the system is capable of maintaining stable, desired response under varying operating conditions in the presence of disturbances, sensor noise, extraneous dynamics or other perturbations without human operator intervention. In the case of MAVs, the added requirement of an autonomous flight control system capable of agile maneuvering flight, challenges the capabilities of even state-of-the-art control theory and design methodology. Because of this, studies of the flight behavior and underlying mechanisms of insect, bird and bat flight may not only provide insight into the dynamics of aeroelastic and propulsive flight, but may motivate development of new flight controller architectures capable of exploiting those dynamics.

A MAV flight control system designed using conventional methods exhibits a kind of compartmented functionality. Similar to an air intercept missile, a MAV might employ a conventional guidance system that consists of an outer guidance loop commanding an inner autopilot loop. The guidance loop generates acceleration commands based upon estimation of the target- or obstacle-to-MAV relative kinematics obtained from on-board camera measurements. The acceleration commands, or somewhat equivalently angle-of-attack and bank angle commands, are inputs to an autopilot that generates control surface deflections to achieve the commands. The autopilot provides the critical function of producing a stable, smooth rigid body airframe response, even in the presence of noise or disturbances. One obvious reason for this functional decomposition lies with simplifying the controller design problem. The relative kinematics and dynamics of a MAV intercept problem involve, at a minimum, an eighteen dimensional state space: the relative position and velocity of the MAV and target, the rigid body translation and rotational velocities of the MAV, the Euler angles relating the rigid body quantities to an inertial frame, and some model of the target acceleration. Add to this the dynamics associated with sensors and actuators, perhaps including structural dynamic models for flexible airframe and control surfaces, and the state space could easily double or triple in dimension.

In general, the control problem would be to solve this complex system of highly nonlinear and coupled dynamics equations for the MAV control deflections to achieve an intercept with an evasive target. For any number of reasons having to do with control theory limitations, practical implementation issues, uncertainties in the dynamics and other issues, this is rarely if ever attempted. The problem can be simplified through time- or frequency-based separation into a relatively high-bandwidth inner stabilization loop and a lower-bandwidth outer guidance loop, treating sensor, actuator and other extraneous dynamics as higher order effects during the controller design. This separation requires that the physical response of the vehicle in its interactions with its surroundings be separable into slow and fast dynamics. While this separation is usual and physically justified in manned aircraft and large UAVs, it may not be applicable to agile autonomous MAVs capable of aggressive maneuvers in confined airspace, where the relative kinematics between a MAV and other nearby objects may be as fast as its body dynamics. Imposing the usual separation of slow and fast dynamics on a MAV guidance system design (that is, reducing its guidance response bandwidth to mitigate coupling with its body dynamics) will result in stable but sluggish vehicles that have only limited agility.[42,43] Interestingly, recent progress in the development of techniques for designing integrated adaptive guidance and control architectures may offer an alternative worth exploring to the usual time-scale separated designs.[44]

This is only the beginning of the control design challenge for MAVs. In conventional flight control systems, the rigid body dynamic response is treated as steady or quasi-steady. It may even be linearized about an operating point (e.g., fixed angle of attack, zero body rates) into longitudinal short period and phugoid, and lateral Dutch-roll, roll subsidence and spiral divergence modes. Whether treated as linear or nonlinear, the rigid body dynamic responses are assumed to be produced by steady aerodynamic forces resulting in stable (or stabilizable) transient airframe motion. Controllers designed to exploit unsteady aerodynamic effects, such as forces that might be generated during the perching maneuver shown in Figure 2, may require much higher fidelity aerodynamics models than those currently used, and/or unconventional aerodynamic sensors such as pressure transducers or flow sensors. For example, in current autopilot designs nominal values of C_{mq}, C_{lr}, and C_{lp} (nondimensional pitch moment due to pitch rate, and roll moment due to yaw and roll moment due to roll rate, respectively) are often included in the design model for synthetic damping to produce a smooth controlled response. As long as their signs and rough orders of magnitude are known, the controller design does not usually require precise values. Still other dynamic derivatives such as $C_{m_{\dot{\alpha}}}$, $C_{n_{\dot{\beta}}}$ and $C_{l_{\dot{\beta}}}$ are often ignored. Whether similar approaches will work for agile MAV autopilot designs has yet to be investigated.

A related issue is open-loop versus closed-loop response. The output of any controlled dynamical system reflects the impact of the controller and control effector dynamics on the nominal system dynamics. So the short period response of a MAV with an autopilot to disturbances such as the wind gust of Figure 4 will, in general, differ from that of the uncontrolled airframe itself. This is, of course, one of the reasons for including an autopilot: the airframe's nominal, open-loop short period motion may be underdamped and too slow for the vehicle to successfully react to commands. With airframes dominated by steady or quasi-steady aerodynamics, reduced order models of the open-loop rigid body dynamics, employed with the tools of modern linear or nonlinear control theory, are often adequate to produce controller designs that yield the desired closed-loop response. Since the presence of significant disturbances, unknown dynamics or large parametric uncertainties may require substantial controller tuning or even redesign to yield an acceptable closed-loop response, considerable effort is spent on refining the dynamics models of high performance airframes. It is unlikely that producing such high fidelity models will be cost effective in the design of MAVs, at least while so many open questions remain as to the fundamental physics. For that reason, recent progress in nonlinear adaptive control techniques that reduce the dependence on high fidelity models need to be explored for MAV flight controller designs.[45,46,47]

As discussed earlier, flexible wings have various properties that may make them very desirable for use on MAVs. Aeroelasticity is a familiar phenomenon to missile and airplane autopilot designers. Long, slim air-intercept missiles exhibit structural dynamics that affect controller performance and stability. Depending on the frequencies and particular modal characteristics, these structural dynamics may enhance or attenuate control effector response or may be erroneously sensed as body rates by the inertial sensors. Considerable effort is expended on mitigating these kinds of effects, since they often result in performance degradation or even instability. If the structural dynamics are of sufficiently high frequency, the controller may be designed to limit the closed-loop response, essentially reducing the response bandwidth so that the rigid body response does not excite the structural modes. If they are of lower frequency, dynamic filters must often be included to produce the required stability robustness at the cost of performance. Because of these issues, most control designers develop the mindset that structural flexibility is undesirable. The possibility of accommodating structural flexibility for its desirable properties, or even of actively exploiting these properties to expand the operating flight envelope of the MAV, offers rich new areas of research, both to revisit existing methodologies and to

spawn new ones. And it is hard to ignore the fact that flexible wings are universally employed by the only agile autonomous airframes flying at these scales: the insects, birds and bats.

5. Biological inspiration in MAV design

Biological inspiration has an impressive and long history, extending perhaps to the roots of human technology. Certainly man's earliest attempts at flight were inspired by observation of birds and bats. But just as high-speed aircraft and missiles bear little resemblance to flying organisms, the tools, techniques and even the physics of large-scale, high-speed flight do not seem to scale to the MAV size regime. Thus, the study of biological flight seems to be a natural route to expansion of the capabilities of agile autonomous MAVs. But ironically the most universal technologies associated with human locomotion, the wheel, the rigid wing and the rotating propeller, are not found in nature's flying organisms. This irony provides a cautionary note that human-engineered systems may have attributes and constraints that, ultimately, preclude biological solutions.

Flying insects display a wide diversity of body morphologies. Many are capable of impressive feats of aerobatic flight. Dragonflies have two pairs of membranous wings independently driven directly by flight muscles. Hoverflies, a kind of dipterous fly, have only a single pair of wings driven indirectly by muscles that rhythmically contract the thorax; the hind wings have become specialized as small body rotation sensors (halteres). Butterflies and moths have two pairs of wings that flap in synchrony, functioning effectively as a single pair of low aspect-ratio wings. Each group contains insects capable of hovering and highly maneuverable flight, apparently achieved by exploiting unsteady aerodynamics produced from precisely controlled wing kinematics. Compound eyes provide wide field-of-view motion sensitivity that, integrated with a variety of body mechanosensors (e.g., halteres in dipterous flies, antennae in moths, and perhaps sensors at the base of the wings themselves in those and other insects) and various proprioceptors and strain sensors distributed throughout the body, provide the necessary feedback for stable controlled flight. The compound eyes, often augmented by small simple eyes (ocelli), provide attitude reference information essential for level flight. The compound eyes also track small targets, often in specialized regions of higher acuity facets, providing the sensory feedback necessary for prey or mate pursuit, for predator evasion or with other sensory modalities for food localization. In addition to the vision system, chemoreceptors, especially in the antennae but also localized in other body regions, and tactile sensory hairs distributed over the body provide insects with a nearly spherical field-of-view sensing capability. A large and growing literature on insect sensing exists. McIver has a good discussion of mechanosensing in insects[48,] and Warrant, et al., provides a fine introduction to insect vision.[49]

Flying birds, ranging in size from tiny hummingbirds to eagles, likewise have impressive flight capabilities. Bird wings are feather-covered, highly modified vertebrate forelimbs in which the wrist and finger bones are fused and reduced in size. The wings, which are deformable due to the elbow and wrist joints and anisotropically flexible due to structural properties of the feathers, are powered by specialized pectoral and coracoid muscles attached to a deeply keeled sternum. Terns have high aspect-ratio wings and fly much like manmade aircraft while soaring but are capable of agile precise flight when picking small fish from the water surface. Eagles, with broad powerful wings, exploit thermals in extended soaring but are capable of aggressive controlled maneuvers in which the wings appear to be in deep stall during takeoff, landing, or prey capture. Falcons can plummet at high speed to snatch a small passerine bird from within a flock, while accurately maneuvering to avoid potentially crippling collisions with other birds in the flock. Hummingbirds, unlike other birds, exhibit insect-like wing kinematics during hover, completely

reversing the upper and lower surfaces during a full wing stroke. Somewhat surprisingly, given the similarity in wing kinematics, unlike insects hummingbirds do not appear to generate lift on the recovery upstroke. All birds have vestibular organs providing body motion information that, perhaps with wing muscle load sensing and probably with input from vision motion sensing, allow for stable controlled flight. High vision acuity in the fovea of the vertebrate eye, cued from peripheral vision motion sensing and other senses, provides vision-dominated sensory systems that allow hummingbirds to feed on flower nectar while hovering and swifts to feed on insects in flight. The well known auditory capabilities of owls represent an elaboration of another sensory modality that is important in all birds.

Bats, the third and evolutionarily most recent example of extant flying organisms, demonstrate flight maneuver capabilities that are at least the equal of those of insects and birds. The wings are skin membrane covered, highly modified vertebrate forelimbs in which the fingers are greatly elongated and flexible, comprising up to half the wing span in some bats. Bat wings are actively deformable from the elbow, wrist, and finger joints and from the aerodynamic loading of an extraordinarily flexible anisotropic membrane covering limb bones and flexible fingers. Flying foxes, with wingspans approaching two meters, locate and feed on fruit in tropical tree canopies. Nectar-feeding bats exhibit hovering behaviors and capabilities comparable to hummingbirds or hoverflies but with dramatic deformations of the wing shape during each stroke. Insectivorous bats likewise exhibit in-flight feeding behaviors comparable to dragonflies, swifts and kestrels but with very different wing motions. Like birds, bats have vestibular organs providing body motion information that, with wing muscle load sensing and probably with input from vision motion sensing, allows for stable controlled flight. High vision acuity in the fovea of the bat's typical vertebrate eye, cued from peripheral vision motion sensing, provides vision-dominated sensory systems in old world bats and augments the extraordinary echolocation systems of new world and many old world bats. As for most mammals, hearing and olfaction are important sensory modalities for all bats.

Several common themes emerge from comparisons of flight in insects, birds and bats. The most obvious of these is flying animals' all but universal reliance on flapping propulsive flight. Given that flapping frequency generally scales inversely with body mass, one might be tempted to conclude that flapping is optimal for airframes operating at small sizes and low flight velocities. Whether and to what extent this is true is, however, a completely open question. Since biological wings evolved from structures once used for other purposes and are powered by muscles, at best they may be optimal in some sense given the constraints imposed by evolutionary history, embryonic development, metabolism and so forth. In any case, given the fact that only flapping organisms currently have the properties of agile autonomous flight at these scales, flapping propulsive flight is certainly worthy of study.

Aeroelasticity and flexibility, both passive and active, seems to be nearly as universal in animal flight as flapping. Wootton[29] has made long study of insect wing flexibility and recent experiments by Combes and Daniel[30] have investigated the relative contributions of aerodynamic forces and inertial dynamics to insect wing flexure during flapping. Numerous researchers have noted aspects of bird wing flexure and speculated on its contribution to flapping or gliding flight, but systematic studies on the vast diversity of bird wing flexibility characteristics have yet to be made. Swartz, Breuer et al.[50,51] are undertaking a careful aerodynamic and structural characterization of bat wing flexure and morphing. These and other studies may soon produce meaningful insight into the importance of structural flexibility, and to the relative importance of passive and active flexure and wing morphing. Still, as with flapping, it is certainly possible that wing flexibility is predicated by biology, and not by the physics of flight in these flow regimes.

Unlike manmade air vehicles, flying organisms are articulated non-rigid bodies. Insects have a head, thorax and abdomen that move relative to one another. Birds and bats have heads connected by highly flexible necks to their bodies. All, of course, have moving wings and moveable legs. While it is unclear whether or to what extent these non-rigid body characteristics

affect flight, anecdotal evidence suggests that, in some cases, they should be explored. Albertani, et al.[52] are conducting high speed video studies of butterflies that flex their abdomens during maneuvering flight (Figure 14). As with flapping and aeroelasticity, the importance of these kinds of non-rigid body dynamic characteristics for MAV-scale flight needs to be more fully explored.
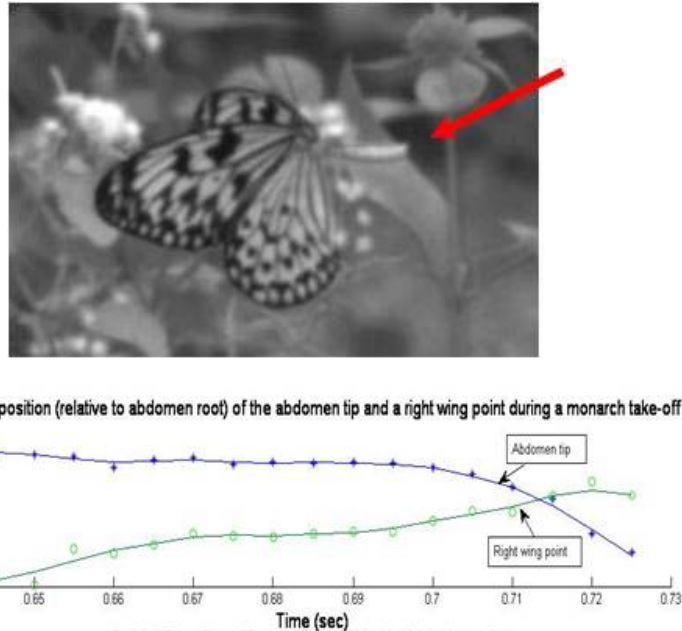
Figure 14. Traces of butterfly right-wing position and abdomen deflection during takeoff.[52]

A final important theme emerging from studies of biological flight should be considered in any attempt to extend attributes of flying organisms to the design of MAVs. Flapping wing propulsive flight, flexible wings and non-rigid body dynamics are all employed by animals that exhibit and are even largely defined by sensory-response systems. It would not be unreasonable to describe any living organism as a complex network of interdependent, multi-scale sensory-response systems. Any passive physical attributes of biological flight are embedded in layers of closed-loop sensory-response systems, some directly associated with flight and most associated with myriad and diverse processes connected with life. Thus questions of function and design principles associated with flight in nature are implicitly questions of the sensory-response characteristics of the animal's flight control system. There is simply no way to separate the mechanical design of an insect, bird or bat wing from the various sensors, neuronal architecture and muscles associated with its use as a lift and propulsive device in the living organism. This is not to say that the mechanical and structural attributes are not important in themselves, but that they evolved in the context of the complex closed-loop sensory-response system of the animal. So the question of what attributes of flexible/flapping wings are desirable for MAVs implies the question of what, if any, sensory and motor-response attributes are required for producing those desirable properties.

This last observation suggests the need for comparative studies when looking to biology for flight attribute inspiration. Reflecting a phenomenon known to biologists as evolutionary convergence, animals with different ancestry often arrive at similar solutions to confront similar problems. Given the conservatism of evolutionary selection mechanisms imposed on modification or elaboration of existing structures, attributes held by unrelated animals are candidates for very good solutions. As a corollary, different solutions to the same problem suggest a large design space. Both are worthy of investigation in the quest for agile autonomous

MAV flight. In fact, comparisons of insect, bird and bat flapping flight have yet to produce a consensus on the key factors accounting for the similarities and differences of their respective flight structures and mechanisms. Thus comparison studies are critical, but woefully underfunded areas of research that should be encouraged if we are to develop a deep understanding of biological flight, and infer from that understanding desirable design characteristics for agile autonomous MAVs.

Conclusion

Micro UAVs are useful to the extent that they are agile in flight. The MAV design problem – and the challenges in the underlying sciences – is how to enable high agility, and how to do so efficiently and robustly. One aspect of agility is high maneuverability and the management of massively-separated, unsteady flows – for example, in gusts and perching maneuvers. Other maneuvers, not considered here, include precision flight around obstacles and executing high rates of turn to follow complex trajectories. One approach towards agility in a systems sense is exploiting airframe structural flexibility. Flight dynamics and control models are being developed that include the effects of flexibility. MAV flight testing holds promise in validating these models, with additional outcomes such as better definition of requirements for the on-board sensors that would be needed to integrate flexibility into the flight control system. Structural flexibility can be modulated to trade for example between gust tolerance and maximizing control derivates. In flapping-wing applications, flexibility greatly expands the design trade space, offering simplicity of actuation and potential for power-savings through resonant actuation. From the engineering point of view, improvement of MAV agility is predicated on combined experiment and computation on a range of configurations, from gross abstractions such as plunging rigid 2D airfoils all the way to performance characterization of flexible flapping-wing flight articles. Parallel studies of biological flight offer additional insight into the MAV agility problem, requiring that engineers and biologists work together in a synergistic study of nature's solutions to some of the most exquisitely complex problems in the flight sciences.

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In-Flight Dynamically Adaptive Configurations: Lessons from Live Lepidoptera

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This paper discusses the collection, post-processing and subsequent evaluation of flight data of butterflies, in various free flight scenarios. A vision tracking system is used to obtain the flight data; and this in turn is used to determine estimates of the motion of different body parts of the insect, including the abdomen and the wings. These estimates are subsequently analyzed with a view to establishing the manner in which the insect adapts the motion of its abdomen to work in tandem with the motion of its wings. Furthermore, the manner in which this adaptation changes through different flight phases is studied.

I.   INTRODUCTION

The aerospace engineering community is increasingly interested in the flight mechanics and dynamics of small flapping air vehicles, Figure 1(a), and natural organisms in the low Reynolds number regime. The

Figure 1. (a) A 20 cm wingspan ornithopter with a flexible wing in the REEF small wind tunnel. (b) The rain forest at the McGuire Center for Lepidoptera and Biodiversity, Gainesville, FL.

observation and study of flying animals offers a significant source of bio-inspiration in several aeronautical disciplines including highly dynamic adaptive structures. While flight measurements of biological systems are relatively abundant, a meaningful recording of the data and an efficient distillation of their results is a work-in-progress endeavor. Comprehensive data on insects flying in their natural environments are extremely rare.

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This paper presents the experimental techniques used for collecting live flight data from Lepidoptera in their natural environment and illustrates results on their significant capabilities to adapt their intricate wings-abdomen-thorax system to a variety of flight conditions including some extremely aggressive non-steady maneuvers.

The flight measurements were performed at the Butterfly Rainforest at the McGuire Center for Lepidoptera and Biodiversity, Figure 1(b), which is a 650 square meter screened vivarium at the Florida Museum of Natural History in Gainesville, FL. This center houses over 460 species of subtropical and tropical plants and trees to support up to 2,000 free-flying butterflies of 120 different species. Natural fliers demonstrate a diverse array of flight capabilities, many of which are poorly understood. NASA established a research project to explore and develop flight technologies inspired by biological systems.[1] Aerodynamic research on flapping insect wings revealed mechanisms such as leading edge vortices (LEVs) and offered design criteria for insect-based flying machines.[2]

There have been numerous research projects performed by the biology community on the flight and structural behavior of insects. Significant research was performed presenting measurements of insects flight data considering the specimen as a multi-body system including head and thorax. For example, in the Calliphora vicina (Blowfly) it was shown that there exists a high level of correlation between the head and thorax movements; these were measured using sensor coils and during the insect's saccades angular rates of a few thousands of degrees per second were observed.[3] A relevant contribution of the abdomen posture on flight control mechanisms was presented in the male of Schistocerca gregaria (Male desert locust) suggesting that the sensory cue evoking the yaw response is a change in the direction of the relative wind, monitored by the cephalic wind receptor hairs.[4] The adaptability of the Lepidoptera to different flight requirements was observed by a non-symmetric passive wing twisting during upstroke and downstroke in the Insecta Papilionoidea[5] and during the highly un-steady take-off phase in the Pieris melete.[6] Using the evolution of neotropical butterflies as a natural experiment, a correlation between body center of gravity position and flight maneuverability was demonstrated focusing on the relative proportions of the thorax and abdomen as well as the palatability characteristics of different species of butterflies.[7] Flight data gathered during previous work on Idea Leuconoe (Tree Nymph) showed an apparently significant abdomen activity in certain flying phases with a significant correlation with the flapping wing and body dynamics.[8]

There has also been prior work done on locusts tethered in a wind tunnel with the objective of studying their longitudinal flight dynamics.[10–12] Force measurements are obtained in the wind tunnel, which are then used to determine stability derivatives of the insect under different relative wind velocities and angles of attack. The literature also comprises of a discussion on the use of CFD based modeling for the purpose of studying insect aerodynamics and flight dynamics.[13] This paper, on the other hand, relies on free flight data - an advantage of this is the ability to study different maneuvering flight phases of the insect; this advantage however is usually tempered by the fact that the accuracy of wind tunnel data is often better than that of free flight data. This work is aimed at determining the mechanisms used by live butterflies at adapting their intricate abdomen and elastic wings system to non-steady flight conditions. These approaches could lead to the development of new flight mechanics strategies for micro and nano air vehicles.

II.   The Experimental Set Up and Post Processing

The design of the data acquisition system (DAQ) was based on two key requirements: being non-obtrusive and having the capability of field measurements, i.e. allowing measurements in the insects' natural environment. A vision-based estimation method is used to study the insect flight with insignificant interference with the natural behavior of the insects. The visual system is composed of two high-speed digital cameras synchronized as a stereo pair, as schematically illustrated in Figure 2(a). A stereo pair of cameras with known parameters and relative pose allows estimation of 3D position of points in space. The measurements were performed under natural sunlight conditions at $100 - 200$ frames per second and resolutions of $800x600$ pixels. Figure 2(b) shows the cameras and computer hardware at their experimental location.

A sequence of pictures of the desired event is captured from both cameras and converted to two videos, one for each camera, using a combination of custom and commercial software. The videos are digitized using a stereoscopy tracking software[15] and accurate camera calibration data in order to perform 3D stereovision estimation of selected points on the target. The tracking software employed uses a 11-point Direct Linear Transformation (DLT) method for calibration.[14] The validation of the data acquisition and post processing methodology, including an estimation of the uncertainties was achieved by using a custom made target

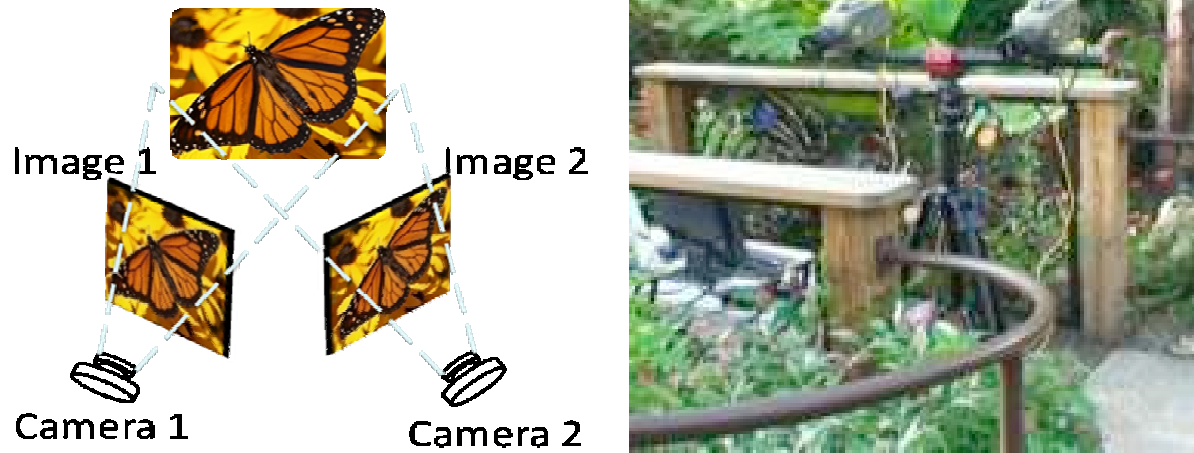American Institute of Aeronautics and Astronautics

Figure 2. (a) The stereo triangulation technique used by the cameras. (b) The stereo cameras in the experimental environment.

consisting of multiple spring-mass components mounted on a shaker. The target has three parts simulating a body, a head and an antenna; and the shaker is controlled by a computer which can induce any desired oscillatory motion to the body. The targets three-dimensional position in time was measured using a high resolution dynamic visual image correlation (VIC) normally used in experimental mechanics.[9] Comparisons with the positions acquired by the tracking software selected for the measurements on butterflies provide estimates of the experimental uncertainties. A sample frame from a video is illustrated in Figure 3, describing an Idea Leuconoe (Tree Nymph) butterfly during an approach for landing on a leaf. In this case a total of four points including the tips of the left and right wings, the tip of the abdomen and the abdomen root, were tracked.
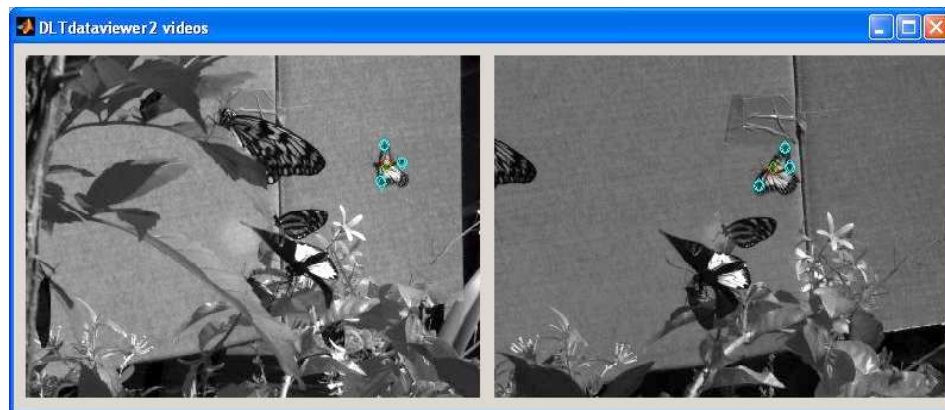
Figure 3. Tracking of body parts of a butterfly during natural flight. Note the tracked points on the wing tips and the abdomen.

The raw data may contain substantial voids due to points on the target being occluded, usually by other body parts or by foliage. Methods of statistical curve-fitting to fill in missing data are used and smooth time histories of the 3D position estimation are obtained, as depicted in Figure 4.
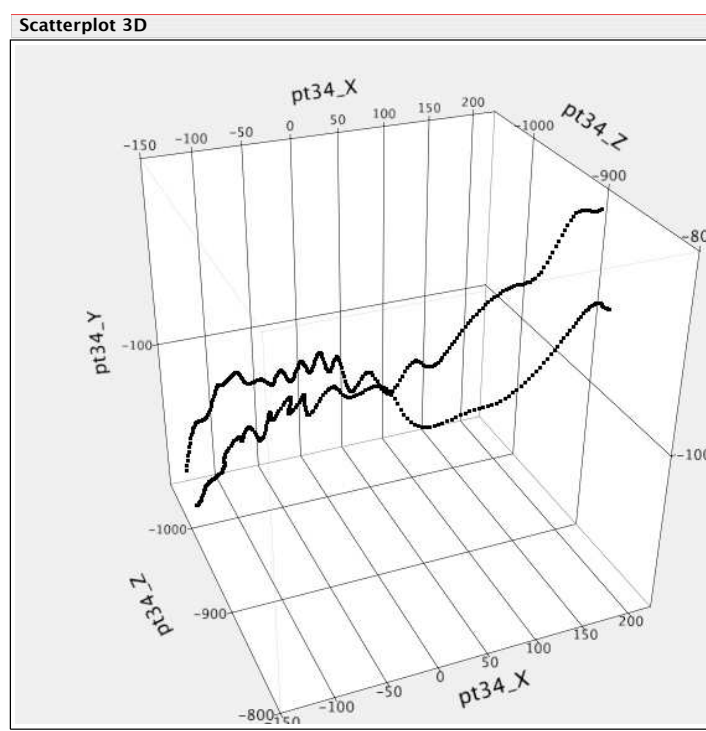
Figure 4. Three-dimensional estimates of wing tips of a butterfly during natural descending flight. The trajectories are depicted after the smoothing process.

III. Results

Data obtained from the live measurements is the processed with several objectives in mind. The kinematics and dynamics of the butterflies' flight are the focus of the flight mechanics segment of the overall project. The shape-changing and relative elastic deformation of the various body parts, specifically the abdomen, the wings, the head and the antennae are the focus of the structural and aeroelastic segment. A combination of these two segments enables the investigation of possible correlations with the overall flight trajectory and performance of the insect. Three samples of the numerous flight events recorded in several sessions will be presented as examples of dynamic in-flight adaptation of the body-wings system.
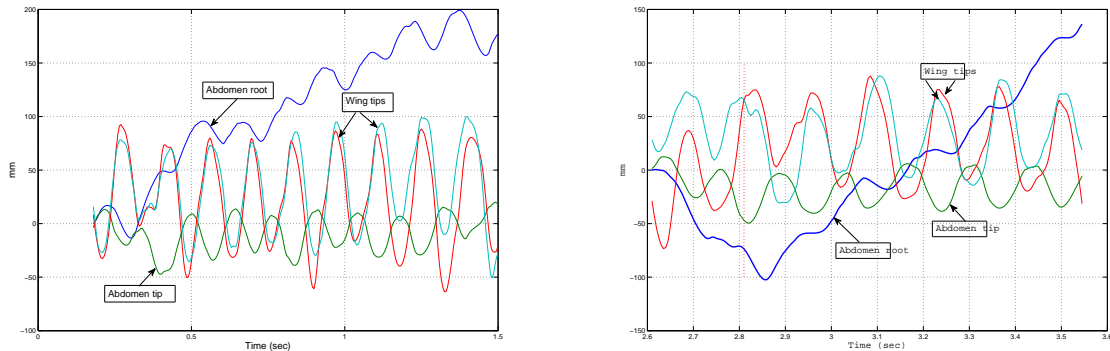
Figure 5. Several flapping cycles of abdomen tip and wings demonstrated during a fly-by sequence

Before we go into a more detailed study of the relative motion of the wings and abdomen in highly maneuvering flight, we briefly present a figure from a slightly benign flight sequence which is of a relatively long duration and that enables us to witness several flapping cycles. This is given in Figure 5, which shows

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the vertical axis position of the wing tips and the abdomen tip relative to the abdomen root.

This figure clearly shows that for all the flapping cycles on display, the abdomen tip motion is nearly 180 deg out of phase with the wing tip motion. Also shown in the figure, is the vertical axis displacement of the abdomen root. In the particular flight sequence shown in Figure 5(a), the insect exhibited some periodicity in its overall flight trajectory, and interestingly the number of cycles of the abdomen root motion is exactly equal to the number of cycles of motion of each of the wing and the abdomen. Furthermore, Figure 5(a) demonstrates what appears to be a clear phase lag of the translational motion of the abdomen root (which represents the overall motion of the insect), relative to the wing and the abdomen tip motion; and this seems to indicate that the insect is using its abdomen as an active control device, at least during this particular flight phase.

The flight discussed above does not comprise of any significantly rapid maneuvers. We now turn our attention to a flight (of an insect from the same species) that does comprise a sequence of rapid maneuvers. More specifically, we now look at a flight that comprises of an acceleration phase, followed by a deceleration, followed by a turn and finally a phase of pure descent. During the 180 degree saccade on a horizontal plane with near zero turning radius the butterfly's abdomen adapts to the wing motion and significantly contributes to the dynamics of the turn. This 180 degree turn in yaw was performed in Flight 072708_0101 by an Idea leuconoe (Tree Nymph). A few snapshots of the flight are given in Figure 6.
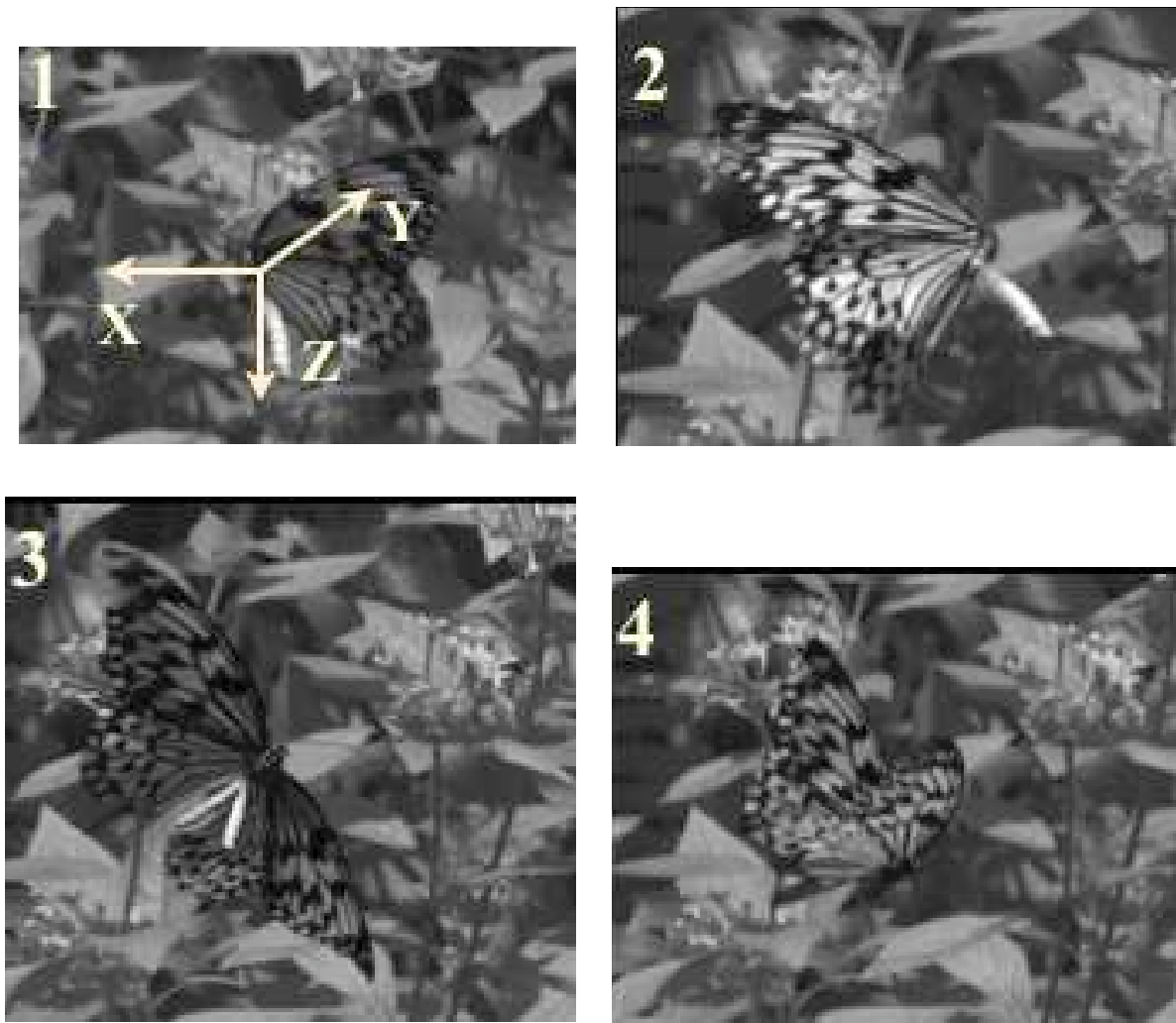
Figure 6. Sequence during the Tree Nymph saccade. In (1) the butterfly starts a rapid deceleration with an aggressive yaw (2) and roll (3) motions. In (4) it starts a steady descent.

The sequence of phases during this flight are as follows:

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a) The insect initially accelerates in the forward direction, while reducing the y-axis component of its velocity to near zero. This is clearly brought out in Figure 7 which shows the insect velocity (which is represented by the velocity of the abdomen root). b) It then decelerates as it readies itself for a turn. In this phase, first the
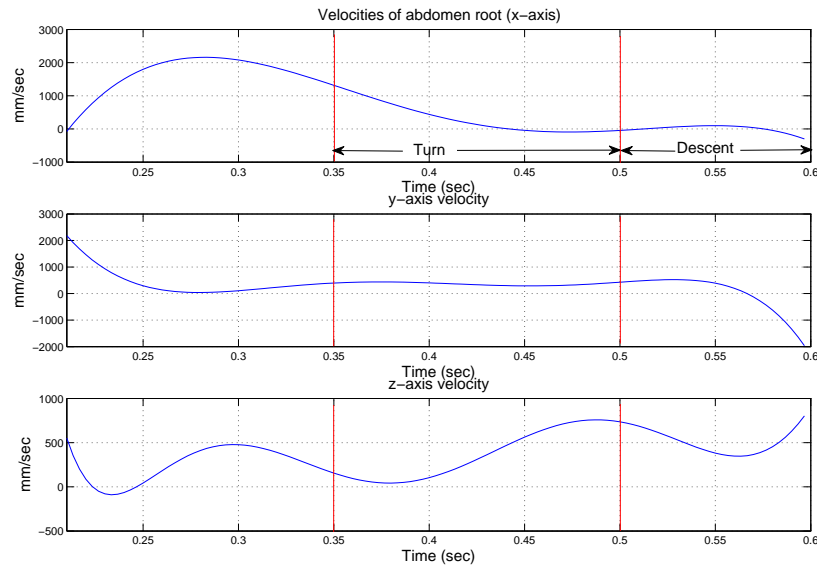
Figure 7. Overall velocity of the insect

forward velocity of abdomen root reduces till it comes down to zero. The abdomen tip however continues to move forward with some velocity. After about 0.1 sec, the forward velocity of abdomen tip too reduces to zero.

c) The head-thorax turns upwards, as the abdomen tip swings around, while the abdomen root performs a yawing turn. This is evident in Figure 8, which shows the trajectory of the abdomen root and the abdomen tip on a horizontal plane. In order to show the relative position of the abdomen root and tip during this trajectory, a line (dotted red) is also shown. One can thus see the motion of the abdomen root is initially curved as it takes a turn and then (its projection on the horizontal plane) moves along a straight line. The abdomen tip however continues to swing around even after the abdomen root has stopped its turn. The abdomen activity also seems to indicate that there is an adaptation of the insect mass-distribution for this small radius maneuver.

d) The wings typically flap in phase in symmetric flight although in this case, around this time, the wing tips are at 180 deg out of phase with each other, while the insect performs a roll. The fact that they become 180 deg out of phase is evidenced in Figure 9.

e) The insect loses altitude as the wing tips take some finite time to get back to flapping in phase with each other. The wing tips take about 0.1 sec to transition from 180 deg out of phase to back in phase. During that time interval, the insect loses close to 100 mm in altitude. All of these are evidenced in Figure 9.

f) As the two wings get back together in phase with one another, at the same time the abdomen tip gets itself back to 180 deg out of phase with the wings, which would represent the normal symmetric flying condition. This is also evidenced in Figure 9. At the beginning of the saccade the insect gives priority to the aerodynamic effects of the wings as well as positioning the abdomen vertically to maximize the drag. At the apex of the saccade the butterfly is using the abdomen inertia to execute a snap-roll and later to stabilize the flapping to go in a descending-hovering mode. The mass and inertia of the relatively heavy abdomen is dynamically adapted for the various phases of saccade. A relevant contribution to the gyration inertia management is also attributed to the wings' moving and closing at strategic times.

Figure 10 demonstrates the left wing tip and abdomen tip trajectories, shown on a vertical plane, relative to the moving abdomen root. The abdomen root is thus always at the origin of this figure. It is clearly seen that as the wing tip moves back and forth, as well as up and down, the abdomen tip too shows a back and forth and up and down motion. The starting points on each of the two curves are marked out

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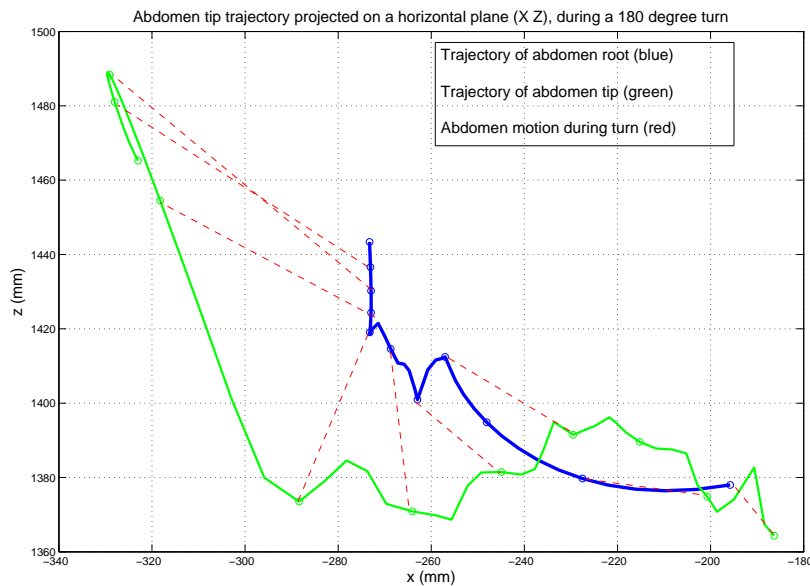
Figure 8. Abdomen root and tip trajectory projected on a horizontal plane during a 180 degree turn.

in small green circles. During the initial acceleration phase, the wing tip executes a stroke that is close to horizontal - this is in agreement with general intuition that horizontal wing strokes would be used for thrust generation. The abdomen tip stroke during this phase has both horizontal as well as vertical components. During the deceleration phase, the insect reduces its wing flapping speed and brings its wing tips high above the abdomen root. There is an accompanying twisting motion of the wings around this time (not visible on Figure 10), as the insect uses its wings as an airbrake of sorts to slow itself down. Simultaneously, it is seen that the insect brings its entire abdomen almost directly under the abdomen root and the horizontal stroke of the abdomen is very short during this phase. This is probably because the insect wants to sustain the abdomen in as close to a vertical position as possible since doing so can ensure that the abdomen contributes to the drag force. It then executes the turn, after which there is a phase of pure descent during which both the wing as well as the abdomen execute an almost vertical stroke.

Figure 10 thus demonstrates that the insect possesses significant abdomen motion to accompany the wing motion. In certain flight phases, such as the deceleration for instance, the role of the abdomen seems to complement that of the wing, as the insect uses both of them in a manner to increase the drag it experiences. In certain other flight phases, such as the turn, the abdomen seems to play a stronger role than the wings in generating the flight trajectory. For the data shown in Figure 10, we compute the flapping velocities of the wing tip and the abdomen tip. The components of these flapping velocities along the three inertial axes are shown in Figure 11(a). It is seen that during the initial acceleration phase, there is significant component of the flapping velocity along the X-axis, which is the direction of flight of the insect; and the same then reduces during the deceleration phase. The flapping velocity component of the abdomen, along the X-axis does not seem to be affected by the fact that the insect is accelerating or decelerating; but it does show the same periodicity as the wing and consistently remains in a phase opposite to that of the wing. During the turn, the X and Y axes flapping velocity components of the abdomen become almost comparable to that of the wing, thus indicating the strong role that the abdomen plays during a turn. Also, along the Y axes, the flapping velocity of the abdomen initially increases in phase with the wing, but this then gets disrupted till the occurrence of the turn, during which period, the abdomen tip velocity becomes nearly opposite in phase to that of the wing. Figure 11(b) then shows the X axis components of the flapping velocities of the wingtip and abdomen tip on a phase plane. The different flight phases are identified by different colors on this plot.

We can then take the scalar sums of the individual velocity components shown in Figure 11(a) to plot the flapping speeds of the wings and the abdomen. This is shown in Figure 12(a). In this figure, we see that the wing flapping speed is significantly higher than that of the abdomen in all phases of flight, except during the
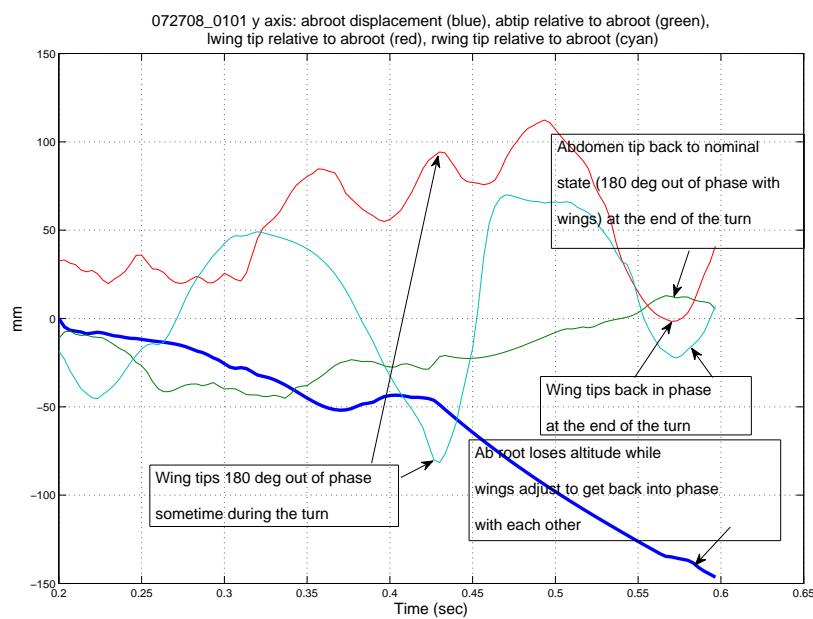
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Figure 9. Vertical axis trajectories of different body parts of the insect.

turn. During the middle of the turn, the amplitude of the peak of the flapping speed is almost exactly equal to that of the wing. Yet by adjusting the relative phases of the two flapping speeds, the insect ensures that the ratio of abdomen tip flapping speed to the wing tip flapping speed is in excess of unity, during the turn. Note that during the initial acceleration and deceleration phases, the abdomen flapping speed varies almost in phase with the wing flapping speed; and it is just at the commencement of, and during the turn that this relative phase pattern gets disrupted. During the second half of the turn, there is an almost constant phase lag of the abdomen tip flapping speed in relation to the wing tip flapping speed. Figure 12(b) then shows the ratio of the abdomen tip flapping speed to the wingtip flapping speed during the different flight phases. It is clearly seen that this ratio becomes significantly high during the turn thus demonstrating the major role that the abdomen appears to play during the turning flight phase, at least as far as this particular ratio metric is concerned.

From the data of Figure 7 and assuming a nominal mass of 0.35 grams, we get the inertial forces acting on the insect. These are given in Figure 13, from which we see that the magnitudes of these forces are of the order of 0.01 Newtons. Figure 14(a) shows a comparison of the Reynolds Number of the wing tip and the abdomen tip through the different flight phases. For this computation, the characteristic length of the abdomen was taken as the abdomen length itself while for the wing, the characteristic length was taken as the mean aerodynamic chord of the wing. Typical values of these quantities for the species being considered are 0.02912 meters and 0.03844 meters, respectively. The diameter of the abdomen is typically 0.00485 meters. The Reynolds Number of the wing tip ranges from 2000 to about 15000, while that of the abdomen tip ranges from 2000 to about 8000. The Reynolds Number of the abdomen is generally lower than that of the wing, except during the acceleration and the turn phases. During these two phases, the Reynolds number of the abdomen tip is comparable to that of the wing tip. Figure 14(b) shows the advance ratio of the wing.

There is significant wing cambering activity as the butterfly prepares itself for the deceleration. This is demonstrated in Figure 15. To generate the plots in this figure, three representative points on the wing chord were tracked - one on the leading edge, a second on the trailing edge and a third in between the leading and trailing edges. In the frames when these three points are found to be nearly collinear, it is construed that there is negligible wing cambering, while at other times it is construed that there is significant wing camber. The wing cambering is demonstrated through a succession of frames, with the abdomen root being positioned at the origin of each of these Figures 15(a-d). In these figures, the color sequence is as follows: the first frame in each figure is represented in blue, followed by green, red, cyan and magenta. Also plotted

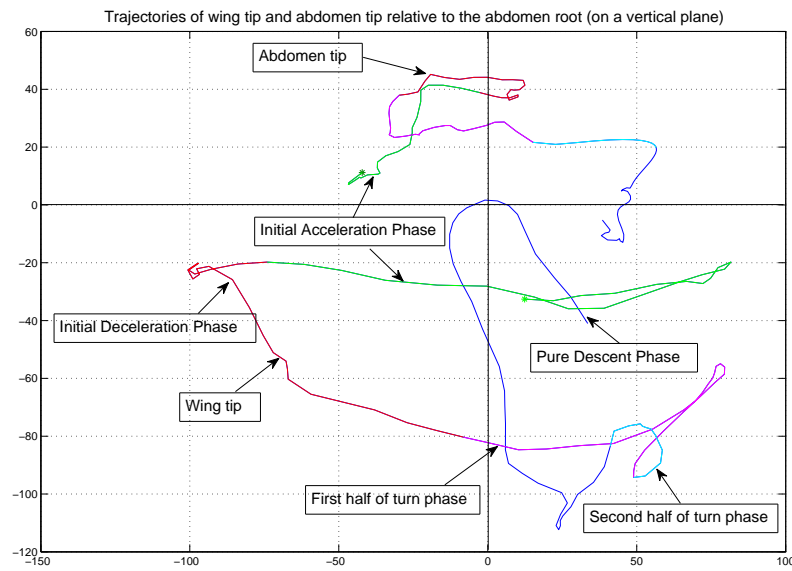American Institute of Aeronautics and Astronautics

Figure 10. Trajectories of left wing tip and abdomen tip shown relative to the abdomen root on a vertical plane. The different flight phases are identified by different colors.

for the purposes of comparison, is the wing tip flapping velocity vector. From Figure 15(a), it is seen that in frame 66, the wing has negligible camber and then progressively gets cambered as it executes a downstroke. Figure 15(b) shows the continued presence of the camber during the wing upstroke motion. Some wing camber continues to be present further along the upstroke; and after the wing crosses the abdomen root, this camber then begins to reduce (as seen in Figure 15(c-d)).

The next relevant example of in-flight structural adaptation is presented with a glide flight with very mild flapping activity (flight number 0330080205). Interestingly enough the event displays an in-flight wings twisting and change of dihedral (on the single wing) with probably no inertia loads from flapping motion on the wing. This fact appears quite remarkable due to the absence of any muscles in the butterfly's wing. Figure 17 illustrates a three-dimensional plot of the trajectory of two chord-wise sections on each wing (right wing blue, left wing green). The absence of significant flapping and the presence of twisting activity are both evident. Again the abdomen (green line) is probably used to dynamically adapt the center-of-gravity position to the new flight requirements (the orientation changes at low rates).
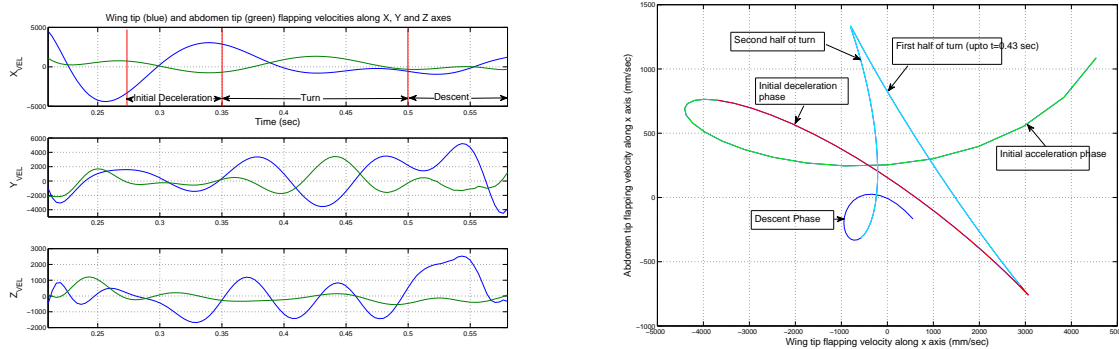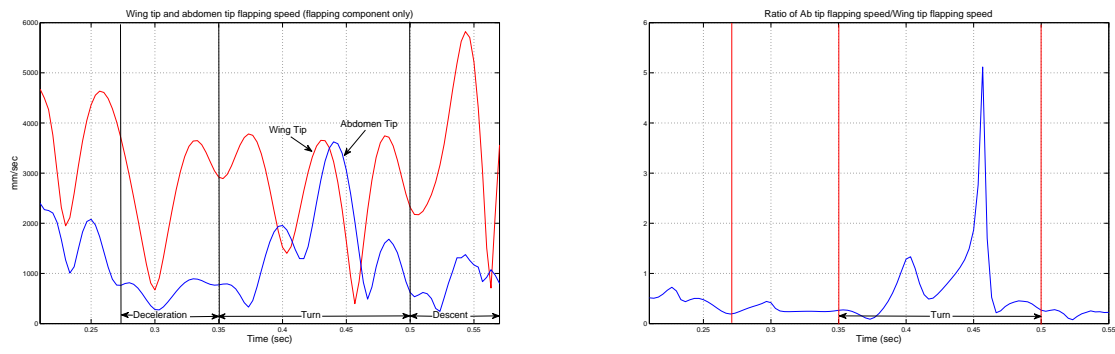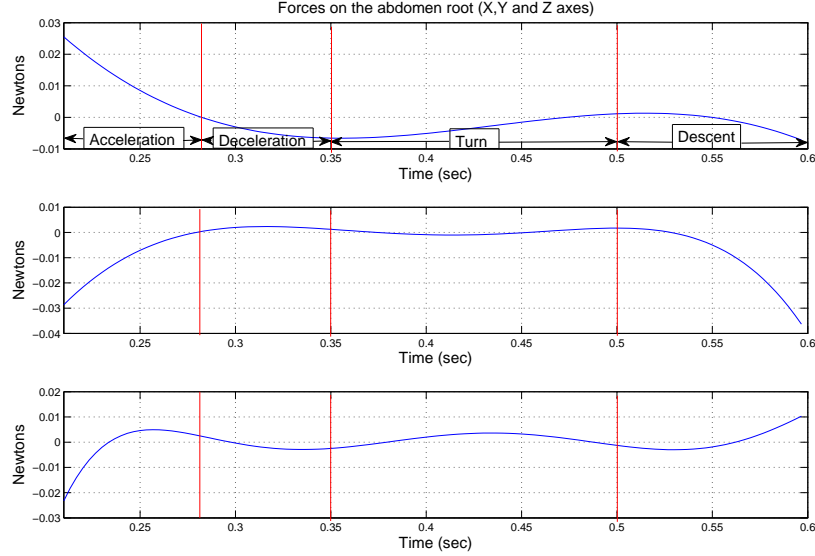

Figure 11. (a) Wing tip and abdomen tip flapping velocities along the X,Y and Z axes. (b) Phase plane plot of wingtip and abdomen tip flapping velocities along the X axis.

Figure 12. (a) Comparison of wing tip and abdomen tip flapping velocities during different flight phases. (b) Ratio of abdomen tip flapping speed to wing tip flapping speed.


Figure 13. Inertial force components on the insect

IV.   Conclusions

This paper discusses the collection and analysis of free flight data of butterflies in their natural environment. A particular flight with several rapid changes in flight phase is evaluated, with the objective being to determine the manner in which the insect adapts the motion of its abdomen to that of its wings; and also to determine how the manner of this adaptation changes from one flight phase to the next. Instances of the insect adapting its wing shape in an aeroelastic manner are also demonstrated. Future work will comprise the use of sophisticated mathematical tools to perform a deeper analysis of this adaptive behavior.

Acknowledgments

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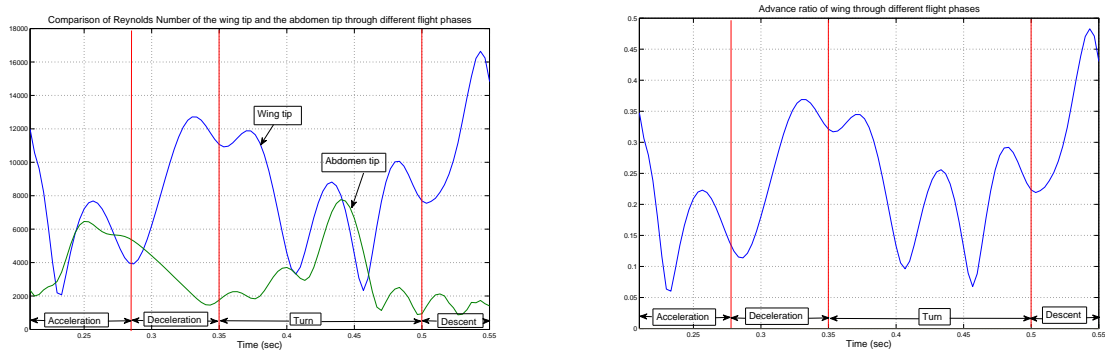
Figure 14. **(a) Comparison of Reynolds numbers of wing tip and abdomen tip through different flight phases. (b) Advance ratio of wing.**

North Carolina, for the use of his tracking software.

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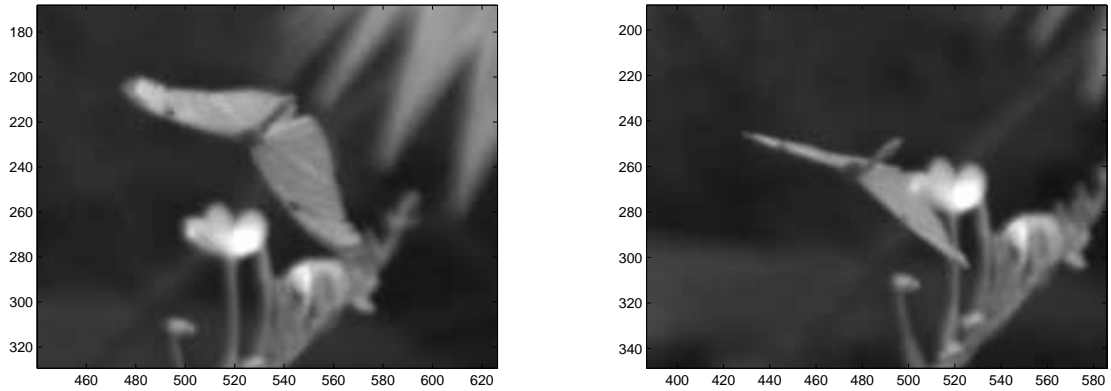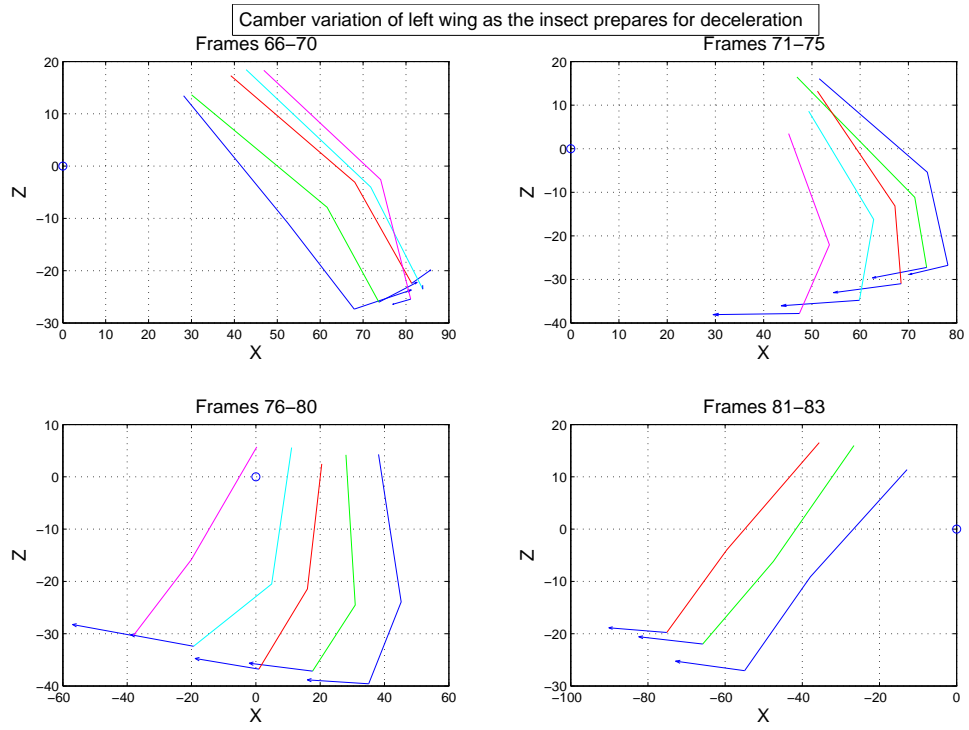Figure 15. Demonstration of wing cambering activity as the butterfly prepares for deceleration.

Figure 16. (a) Snapshot frame demonstrating insect flight with wing dihedral. (b) Snapshot frame demonstrating insect flight with no wing dihedral.
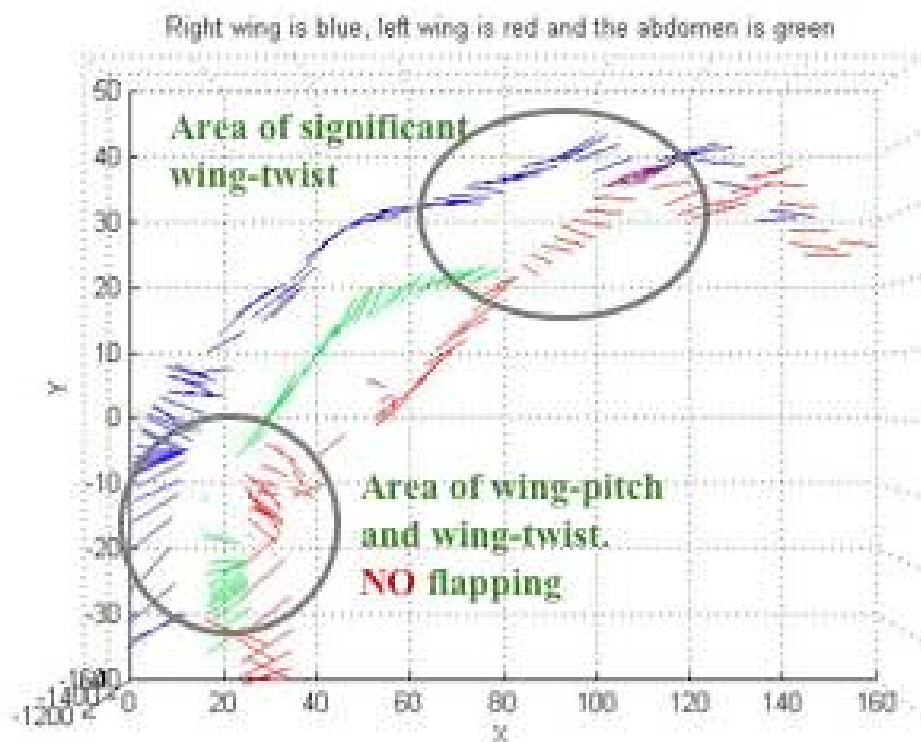
Figure 17. Sequence during a steady descending glide with little flapping activity. The segments represent the right wing chord at mid-wing (blue), the left wing chord (red) and abdomen (green).

Sensitivities and Functional Gains for a Flexible Aircraft-Inspired Model

Animesh Chakravarthy, Katie A. Evans, and Johnny Evers

Abstract— Aeroelastic wing micro-autonomous aerial systems (MAAS) concepts are being explored for military and civilian applications. However, on the whole, the issues of control of MAAS are largely unexplored. Controllers designed using methods applicable to larger aircraft are unlikely to realize the agile flight potential of flexible wing MAAS airframes. In this paper, the authors use two Euler-Bernoulli beams connected to a rigid mass to model an aeroelastic wing MAAS. They employ Continuous Sensitivity Equation Methods to examine the sensitivity of the controlled state with respect to variation of the H_∞ control parameter, with the primary goal being to gain insight into the flexible dynamics of the system in order to exploit the flexibility for control purposes. Further, the authors examine functional gains in order to determine optimal sensor placement while taking advantage of the flexibility of the MAAS model.

I. INTRODUCTION

Considerable work is currently underway to investigate the aerodynamics, structural dynamics, flight mechanics, and control associated with bio-inspired flight (see for example [1], [2], [3], [4], [5]). Consequently, aeroelastic wing micro-autonomous aerial systems (MAAS) concepts are being explored for military and civilian applications. Work from other projects (see for example [6], [7], [8], [9]) is laying the foundation required to eventually construct high fidelity dynamics models of MAAS, which do not currently exist, though key features of such models are emerging. However, on the whole the issues of control of agile aeroelastic wing MAAS are largely unexplored. All micro-scale vehicles developed to date exhibit only limited autonomy, generally way-point trajectory following, with limited agility.

In this paper, the authors use two Euler-Bernoulli beams connected to a rigid mass in an initial effort to model an aeroelastic wing MAAS. Each beam represents a flexible wing, while the rigid mass represents the fuselage. This "beam-mass-beam" model will be referred to as the BMB model system in this paper. The authors employ Continuous Sensitivity Equation Methods to examine the sensitivity of the controlled state with respect to variation of the H_∞ control

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parameter, with the goal being to gain insight into the flexible dynamics of the system in order to exploit the flexibility for control design purposes. A secondary goal of this aspect of the research is to explore the possibility of determining an efficient assignment of the H_∞ control parameter that is mathematically justified and does not require an iterative procedure for determination. Chen identified the problem of finding an optimal value for the control design parameter as an unsolved problem in systems and control theory [10]. Further, the authors examine both controller and observer functional gains in order to obtain insight into the problem of optimal actuator and sensor placement for MAAS systems. The approaches explored numerically in this paper seek to take advantage of the flexibility of aeroelastic wings and exploit the same to achieve agility as opposed to viewing this characteristic as a hindrance for control design.

The outline of the paper is as follows. The H_∞ controller is summarized in Section II. Section III provides a description of the equations governing the partial differential equation (PDE) model, along with the variational forms of the PDE equations and state sensitivity. Numerical results are presented in Section IV. Conclusions and directions for future work are given in Section V.

II. H_∞ CONTROL DESIGN

In this section, the authors present a short overview of the H_∞ compensator design in state space form [11], [12]. Assume the existence of a linear PDE system of the form

$$\begin{aligned} \dot{x}(t) &= \mathscr{A}x(t) + \mathscr{B}u(t), \\ x(0) &= x_0, \end{aligned} \tag{1}$$

where $x(t) = x(t, \cdot) \in X$ is the state of the linear system and X is a Hilbert space. Here, $\mathscr{A}$ is the system operator defined on $\mathbf{D}(\mathscr{A}) \subseteq X$ that, by assumption, generates an exponentially stable C_0 semigroup, $\mathscr{B}$ is the control operator, and $u(t)$ is the control input, defined on Hilbert space U, which is taken to be $\mathbb{R}^m$ in this work. It is assumed that knowledge of only part of the system can be obtained through the state measurement y on Hilbert space Y, which is taken to be $\mathbb{R}^p$ in this work, where

$$y(t) = \mathscr{C}x(t). \tag{2}$$

Assume an estimate of the state is used in the control law. To provide this estimate, a compensator is used that has the form

$$\dot{x}_c(t) = \mathscr{A}_c x_c(t) + \mathscr{F}y(t), \quad x_c(0) = x_{c_0} \tag{3}$$

and the feedback control law is written

$$u(t) = -\mathscr{K} x_c(t) \quad (4)$$

where $x_c(t) = x_c(t,\cdot) \in X$ is the state estimate. Designing a controller of this type requires determining $\mathscr{A}_c, \mathscr{F}$, and $\mathscr{K}$. By solving the Riccati equations

$$\mathscr{A}^*\Pi + \Pi\mathscr{A} - \Pi(\mathscr{B}R^{-1}\mathscr{B}^* - \theta^2\mathscr{B}\mathscr{B}^*)\Pi + \mathscr{C}^*\mathscr{C} = 0, \quad (5)$$

where $R : U \to U$ is a weighting operator for the control of the form $R = cI$, with c a scalar and I the identity operator, and

$$\mathscr{A}P + P\mathscr{A}^* - P(\mathscr{C}^*\mathscr{C} - \theta^2\mathscr{C}^*\mathscr{C})P + \mathscr{B}\mathscr{B}^* = 0, \quad (6)$$

one can obtain the operators $\mathscr{K}$, $\mathscr{F}$, and $\mathscr{A}_c$ via

$$\begin{aligned}
\mathscr{K} &= R^{-1}\mathscr{B}^*\Pi, \\
\mathscr{F} &= (I - \theta^2 P\Pi)^{-1}P\mathscr{C}^*, \\
\mathscr{A}_c &= \mathscr{A} - \mathscr{B}\mathscr{K} - \mathscr{F}\mathscr{C} + \theta^2\mathscr{B}\mathscr{B}^*\Pi.
\end{aligned} \quad (7)$$

The resulting feedback control is applied to the original linear system; the closed loop linear system is then defined by

$$\frac{d}{dt}\begin{bmatrix} x(t) \\ x_c(t) \end{bmatrix} = \begin{bmatrix} \mathscr{A} & -\mathscr{B}\mathscr{K} \\ \mathscr{F}\mathscr{C} & \mathscr{A}_c \end{bmatrix} \begin{bmatrix} x(t) \\ x_c(t) \end{bmatrix}. \quad (8)$$

For sufficiently small θ, there are guaranteed minimal solutions Π and P to (5) and (6), respectively, such that $(I - \theta^2 P\Pi)$ is positive definite and the linear closed loop system (8) is stable. Note that $\theta = 0$ yields the classical Linear Quadratic Gaussian (LQG) compensator design. Since there exist no prescribed formulas for θ, there is an inherent computational expense for this control design in choosing the parameter value. As a secondary goal, the authors seek to use sensitivity analysis to gain a better understanding of the H_∞ controller. The goal is to develop a methodology for choosing θ to satisfy performance and robustness criteria, while justifying that choice based on the analysis. To this end, sensitivity analysis is applied to H_∞ controlled distributed parameter systems to examine the sensitivity of the controlled state to θ.

For certain PDEs, the control law in (4) can be written in integral form. That is,

$$u(t) = -\mathscr{K} x_c(t) = -\langle k_i(s), x_c(t)\rangle_X, \quad (9)$$

for spatial variable s and where $k_i \in X$ for $i = 1, 2, ..., m$ (see for example [13]), and the kernels of the integrals, $k_i(s)$, are called control functional gains. Control functional gains can be used to determine optimal sensor placement (see for example [14], [15], [16], [17]) because they provide information about the contribution of the state estimate to the overall controller. For example, an area where a control functional gain is large would indicate that area provides a state estimate value that contributes more significantly to the controller. Further, there would be potential benefit in placing sensors in that area.

Additionally, the observer gain operator $F : \mathbb{R}^p \to X$ is continuous and has range in $\mathbf{D}(\mathscr{A}) \subseteq X$. Then, for a state estimate of the form $x_c(t) = [w_c(t,\cdot) \quad \frac{\partial}{\partial t}w_c(t,\cdot)]$, F has the representation

$$Fy = \begin{bmatrix} g_1(s) & \cdots & g_p(s) \\ h_1(s) & \cdots & h_p(s) \end{bmatrix} \begin{bmatrix} y_1 \\ \vdots \\ y_p \end{bmatrix} \in X, \quad (10)$$

where $g_1(s), ..., g_p(s), h_1(s), ..., h_p(s)$ are called observer functional gains. To more completely analyze the problem of sensor placement, observer functional gains should be examined alongside control functional gains. For example, an area where an observer functional gain is large would indicate that area provides a measurement value of the state that contributes more significantly to the overall controller design. Thus, using similar logic applied in the case of control functional gains, there would be potential benefit in placing sensors in that area.

As documented in [14], this simple approach to sensor placement does not take into account issues such as performance and robustness. However, given the complex nature and relative lack of understanding of aeroelastic wing MAAS, it is reasonable to examine the functional gains in this problem as initial work toward the direction of designing sensors for these aircraft.

III. AN AIRCRAFT-INSPIRED MODEL

In this work two Euler-Bernoulli beams connected on either side of a rigid mass are used to model an aeroelastic wing MAAS, hereafter referred to as the BMB system. The fuselage of the MAAS is assumed to be rigid. A schematic of the BMB system is given in Figure 1. Note that the BMB system is meant to represent primarily the heave dynamics of the MAAS. The MAAS is initially assumed to be flying with wings straight and level and in equilibrium with the lift balancing the weight. At time $t = 0$, there is assumed to be a perturbation in the wings' shape (caused by a sudden gust, for example). This perturbed wing shape causes a change in the local angle of attack distribution over each wing and this in turn leads to a perturbation in the lift distribution denoted by $\Delta\text{Lift}(t,s)$. Each beam is modeled with both viscous and Kelvin-Voigt damping, and it is assumed that the material and inertial properties of both beams are homogenous and identical. Denoting the displacement of the left beam from its initial equilibrium position at time t and position s by $w_L(t,s)$ and the corresponding displacement of the right beam at time t and position s by $w_R(t,s)$, the model of the BMB system is described as follows:

$$\begin{aligned}
&\rho a \frac{\partial^2}{\partial t^2}w_L(t,s) + EI\frac{\partial^4}{\partial s^4}w_L(t,s) + \gamma_1\frac{\partial}{\partial t}w_L(t,s) \\
&\quad + \gamma_2 I\frac{\partial^5}{\partial t\partial s^4}w_L(t,s) = \frac{-\Delta\text{Lift}(t,s)}{\ell/2} + b_L(s)u_L(t),
\end{aligned} \quad (11)$$

for $0 \le s \le \ell/2$, $t > 0$, and

$$\begin{aligned}
&\rho a\frac{\partial^2}{\partial t^2}w_R(t,s) + EI\frac{\partial^4}{\partial s^4}w_R(t,s) + \gamma_1\frac{\partial}{\partial t}w_R(t,s) \\
&\quad + \gamma_2 I\frac{\partial^5}{\partial t\partial s^4}w_R(t,s) = \frac{-\Delta\text{Lift}(t,s)}{\ell/2} + b_R(s)u_R(t),
\end{aligned} \quad (12)$$

for $\ell/2 < s \le \ell$, $t > 0$, subject to boundary conditions

$$EI\frac{\partial^2}{\partial s^2}w_L(t,0) + \gamma_2 I\frac{\partial^3}{\partial t\partial s^2}w_L(t,0) = 0,$$

$$EI\frac{\partial^3}{\partial s^3}w_L(t,0) + \gamma_2 I\frac{\partial^4}{\partial t\partial s^3}w_L(t,0) = 0,$$

$$EI\frac{\partial^2}{\partial s^2}w_R(t,\ell) + \gamma_2 I\frac{\partial^3}{\partial t\partial s^2}w_R(t,\ell) = 0,$$

$$EI\frac{\partial^3}{\partial s^3}w_R(t,\ell) + \gamma_2 I\frac{\partial^4}{\partial t\partial s^3}w_R(t,\ell) = 0,$$

$$EI\frac{\partial^3}{\partial s^3}w_L(t,\ell/2) + \gamma_2 I\frac{\partial^4}{\partial t\partial s^3}w_L(t,\ell/2)$$

$$-EI\frac{\partial^3}{\partial s^3}w_R(t,\ell/2) - \gamma_2 I\frac{\partial^4}{\partial t\partial s^3}w_R(t,\ell/2) \qquad (13)$$

$$= m\frac{\partial^2}{\partial t^2}w_L(t,\ell/2),$$

$$w_L(t,\ell/2) = w_R(t,\ell/2),$$

$$\frac{\partial}{\partial s}w_L(t,\ell/2) = \frac{\partial}{\partial s}w_R(t,\ell/2),$$

$$EI\frac{\partial^2}{\partial s^2}w_L(t,\ell/2) + \gamma_2 I\frac{\partial^3}{\partial t\partial s^2}w_L(t,\ell/2)$$

$$-EI\frac{\partial^2}{\partial s^2}w_R(t,\ell/2) - \gamma_2 I\frac{\partial^3}{\partial t\partial s^2}w_R(t,\ell/2)$$

$$= I_z\frac{\partial^3}{\partial t^2\partial s}w_R(t,\ell/2),$$

where ρ is the density of the beam material, a is the cross-sectional area of the beam, E is Young's modulus, I is the area moment of inertia of the beam, I_z is the mass moment of inertia of the rigid mass, γ_1 is the coefficient of viscous damping, γ_2 is the coefficient of Kelvin-Voigt damping, m is the mass of the rigid connection between the beams, $b_L(s)$ is the control input function for the left beam, $u_L(t)$ is the controller for the left beam, $b_R(s)$ is the control input function for the right beam, $u_R(t)$ is the controller for the right beam, and $\Delta\text{Lift}(t,s)$ is the function representing the perturbed lift force on each of the beams.
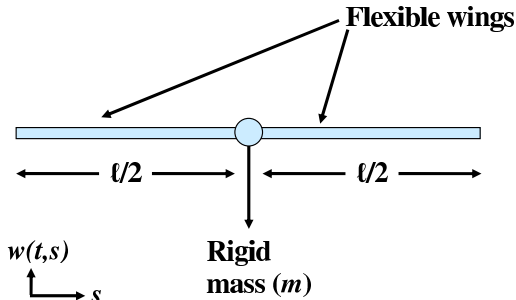

Fig. 1.   MAAS model system.

Sensed information is used to design a feedback controller that regulates the MAAS model system to the exponentially stable zero equilibrium. It is assumed that the controllers act over the entire beam structures with control input functions

of the form

$$b(s) = b_L(s) = b_R(s) = 0.5, \qquad (14)$$

for $0 \le s \le \ell$, and available observations taking the form

$$y(t) = 0.25w(t,s), \qquad (15)$$

for $0 \le s \le \ell$.

A. Variational Form and Discretization of BMB System

Now consider the variational form of the BMB system in order to develop a Galerkin finite element approximation of the problem. For brevity, only the weak formulation of the left beam will be presented; the formulation for the right beam follows similarly. Employing the shorthand notation $\dot{w}(t,s) = \frac{\partial}{\partial t}w(t,s)$ and $w'(t,s) = \frac{\partial}{\partial s}w(t,s)$ for this discussion, the variational problem is that one seeks a $w_L(s) \in V = \{\varphi(\cdot) \in E\} \subset E = H^2(0,\ell/2)$ such that for all $\varphi \in V$

$$\int_0^{\ell/2}\rho a\ddot{w}_L(t,s)\varphi(s)\ ds + \int_0^{\ell/2}EIw_L''''(t,s)\varphi(s)\ ds +$$

$$\int_0^{\ell/2}\gamma_1\dot{w}_L(t,s)\varphi(s)\ ds + \int_0^{\ell/2}\gamma_2 I\dot{w}_L''''(t,s)\varphi(s)\ ds \qquad (16)$$

$$= \int_0^{\ell/2}\frac{-\Delta\text{Lift}(t,s)}{\ell/2}\varphi(s)\ ds + \int_0^{\ell/2}b_L(s)\varphi(s)u_L(t)\ ds.$$

Now choose a basis $\{b_i\}_{i=1}^N$ for the approximating space $V^N \subseteq V$, where N corresponds to the number of gridpoints used in the finite element approximation. In particular, since $V^N \subseteq V \subset E = H^2(0,\ell/2)$, the state can be approximated by a linear combination of cubic splines. Then the state is approximated as

$$w_L(t,s) \approx w_L^N(t,s) = \sum_{i=1}^N c_i(t)b_i(s). \qquad (17)$$

Using the state approximation (17) in (16) yields the matrix equation

$$M_0\ddot{c}(t) + D_0\dot{c}(t) + K_0c(t) = F_0(c(t)) + B_0u_L(t) \qquad (18)$$

where $c(t) = [c_1(t),\ldots,c_N(t)]^T$, M_0 is the mass matrix, D_0 is the damping matrix, K_0 is the stiffness matrix, $F_0(c(t))$ contains the lift function, and B_0 is the input matrix, all defined by the following, for $i,j = 1,\ldots,N$:

$$[M_0]_{i,j} = \int_0^{\ell/2}\rho ab_i(s)b_j(s)\ ds + mb_i(\ell/2)b_j(\ell/2)$$
$$-Ib_i'(\ell/2)b_j'(\ell/2),$$

$$[D_0]_{i,j} = \int_0^{\ell/2}\gamma_1 b_i(s)b_j(s)\ ds$$
$$+ \int_0^{\ell/2}\gamma_2 Ib_i''(s)b_j''(s)\ ds,$$

$$[K_0]_{i,j} = \int_0^{\ell/2}EIb_i''(s)b_j''(s)\ ds,$$

$$[F_0(c(t))]_j = \int_0^{\ell/2}\frac{-\Delta\text{Lift}(t,s)}{\ell/2}b_j(s)\ ds,$$

$$[B_0]_j = \int_0^{\ell/2}b(s)b_j(s)\ ds.$$

Convert (18) into a first order system by defining $x_1(t) = c(t)$ and $x_2(t) = \dot{x}_1(t) = \dot{c}(t)$, thereby yielding

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & I \\ -M_0^{-1}K_0 & -M_0^{-1}D_0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}$$
$$+ \begin{bmatrix} 0 \\ M_0^{-1}B_0 \end{bmatrix} u_L(t) + \begin{bmatrix} 0 \\ M_0^{-1}F_0(w(t)) \end{bmatrix}, \quad (20)$$

$$x(0) = x_0,$$

where $x = [x_1(t), x_2(t)]^T = [x_1(t), \frac{d}{dt}x_1(t)]^T$. Note that (20) is a finite-dimensional approximation of the system in (1).

B. Variational Form and Discretization of Sensitivity Equation for BMB System

This framework now provides the basis for implementing control techniques discussed in Section II. Beyond control design, the authors are interested in examining the effects of the H_∞ control parameter, θ, on the displacement of the beams and the controller itself. The dependence of these quantities on θ is denoted explicitly with the following notation: $w_L(t,s) = w_L(t,s;\theta)$ and $u_L(t) = u_L(t;\theta)$, respectively. Continuous Sensitivity Equation Methods are employed for examining the sensitivities of these quantities to changes in the value of θ used in the H_∞ control design. Make the following definitions for the sensitivities: $s_{w_L}(t,s;\theta) = \frac{\partial}{\partial\theta}w_L(t,s;\theta)$ for the sensitivity of beam displacement with respect to θ at time t and spatial location s and $s_{u_L}(t;\theta) = \frac{\partial}{\partial\theta}u_L(t;\theta)$ for the sensitivity of the controller with respect to θ at time t.

Now derive the variational form of the sensitivity equation by differentiating (11) with respect to θ. One seeks a $w_L(s) \in V = \{\varphi(\cdot) \in E\} \subset E = H^2(0,\ell/2)$ such that for all $\varphi \in V$

$$\int_0^{\ell/2} \rho a \ddot{s}_{w_L}(t,s)\varphi(s)\,ds + \int_0^{\ell/2} EI s_{w_L}''''(t,s)\varphi(s)\,ds +$$
$$\int_0^{\ell/2} \gamma_1 \dot{s}_{w_L}(t,s)\varphi(s)\,ds + \int_0^{\ell/2} \gamma_2 I \dot{s}_{w_L}''''(t,s)\varphi(s)\,ds$$
$$= \int_0^{\ell/2} \frac{d}{dw}\left(\frac{-\Delta\text{Lift}(t,s)}{\ell/2}\right)s_{w_L}(t,s)\varphi(s)\,ds + \quad (21)$$
$$\int_0^{\ell/2} b_L(s)\varphi(s)s_{u_L}(t)\,ds.$$

Choose the same basis $\{b_i\}_{i=1}^N$ for the approximating space $V^N \subseteq V$ as was used in the state approximation. Then the state sensitivity is approximated as

$$s_{w_L}(t,s;\theta) \approx s_{w_L}^N(t,s;\theta) = \sum_{i=1}^N s_{c_i}(t)b_i(s), \quad (22)$$

and a finite dimensional approximation of (21) can be rewritten as a matrix equation

$$M_0\ddot{s}_c(t) + D_0\dot{s}_c(t) + K_0 s_c(t)$$
$$= F_1(c(t), s_c(t)) + B_0 s_u(t;\theta), \quad (23)$$
$$s_c(0) = s_{c0}, \qquad \dot{s}_c(0) = s_{c1},$$

where $s_c(t) = [s_{c1}(t), \ldots, s_{cN}(t)]^T$, M_0, D_0, K_0, and B_0 are defined in (19), and $F_1(c(t), s_c(t))$ is based upon the lift

function. Convert (23) into a first order system by defining $s_{x1}(t) = s_c(t)$ and $s_{x2}(t) = \dot{s}_{x1}(t) = \dot{s}_c(t)$, thereby yielding

$$\begin{bmatrix} \dot{s}_{x1}(t) \\ \dot{s}_{x2}(t) \end{bmatrix} = \begin{bmatrix} 0 & I \\ -M_0^{-1}K_0 & -M_0^{-1}D_0 \end{bmatrix} \begin{bmatrix} s_{x1}(t) \\ s_{x2}(t) \end{bmatrix}$$
$$+ \begin{bmatrix} 0 \\ M_0^{-1}B_0 \end{bmatrix} s_{u_L}(t) + \begin{bmatrix} 0 \\ M_0^{-1}F_1(w_L(t), s_{w_L}(t)) \end{bmatrix}, \quad (24)$$
$$s(x0) = s_{x0},$$

where $s_x = [s_{x1}(t), s_{x2}(t)]^T = [s_{x1}(t), \frac{d}{dt}s_{x1}(t)]^T$. Combining (20) and (24) yields the coupled system

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{s}_{x1}(t) \\ \dot{s}_{x2}(t) \end{bmatrix} = \begin{bmatrix} 0 & I & 0 & 0 \\ H_1 & H_2 & 0 & 0 \\ 0 & 0 & 0 & I \\ 0 & 0 & H_1 & H_2 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ s_{x1}(t) \\ s_{x2}(t) \end{bmatrix}$$
$$+ \begin{bmatrix} 0 \\ H_3\,u(t) \\ 0 \\ H_3\,s_u(t) \end{bmatrix} + \begin{bmatrix} 0 \\ H_4 \\ 0 \\ H_5 \end{bmatrix}, \quad (25)$$

where I is the identity operator and

$$\begin{aligned} H_1 &= -M_0^{-1}K_0 \\ H_2 &= -M_0^{-1}D_0 \\ H_3 &= M_0^{-1}B_0 \quad (26) \\ H_4 &= M_0^{-1}F_0(w(t)) \\ H_5 &= M_0^{-1}F_1(w(t), s_w(t)). \end{aligned}$$

Now, (25) is a finite-dimensional approximation to a system similar to the form of (1), where the additional terms appear due to the coupled sensitivity equation. One can replace the control $u_L(t)$ in (25) by the full state feedback control law

$$u_L(t;\theta) = -\mathcal{K}x(t;\theta) = -\mathcal{K}\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}. \quad (27)$$

Furthermore, one can differentiate (27) with respect to θ to compute $s_{u_L}(t;\theta)$ as follows

$$\begin{aligned} s_{u_L}(t;\theta) &= \frac{d}{d\theta}u_L(t;\theta) \\ &= -R^{-1}\mathcal{B}^*\Pi\frac{dx(t;\theta)}{d\theta} - R^{-1}\mathcal{B}^*\frac{d\Pi}{d\theta}x(t;\theta) \quad (28) \\ &= -\mathcal{K}s_{w_L}(t;\theta) - R^{-1}\mathcal{B}^*\frac{d\Pi}{d\theta}w_L(t;\theta), \end{aligned}$$

where the sensitivity of Π with respect to θ, $\frac{d\Pi}{d\theta}$, is computed by differentiating (5) with respect to θ and solving a resulting Lyapunov equation [18], [19].

IV. NUMERICAL RESULTS

To obtain a solution to the system in (25), initial conditions are chosen of the form

$$\begin{bmatrix} x_1(0) \\ x_2(0) \\ s_{x1}(0) \\ s_{x2}(0) \end{bmatrix} = \begin{bmatrix} \sin\left(\frac{\pi s}{\ell}\right) \\ \frac{\pi}{\ell}\cos\left(\frac{\pi s}{\ell}\right) \\ 0.75 * x_1(0) \\ 0.75 * x_2(0) \end{bmatrix}. \quad (29)$$

TABLE I
SYSTEM PARAMETERS

Parameter	Value	Units
ℓ	10	m
ρ	5.24	kg/m^3
$\hat{w}$, width	$1/\sqrt{48}$	m
h, height	$1/\sqrt{48}$	m
$a = \hat{w}h$	1/48	m^2
E	1.44×10^9	N/m^2
I	1/1327104	kg m^2
m	5	kg
γ_1	0.025	kg/(m s)
γ_2	1×10^4	kg/(m^5 sec)

Fig. 2.   Uncontrolled Position State

That is, to generate a nonzero state sensitivity, the authors choose the initial conditions for the sensitivity equation to be 75% of the initial conditions for the state equation. A finite element approximation using Hermite interpolating cubic splines of order $N = 20$ for the spatial discretization of *each* beam is employed to simulate (25), and the parameter values for the BMB system are provided in Table I. Originally, standard 4 degree of freedom beam elements were selected for the finite element approximation, where the degrees of freedom correspond to displacements and slopes at the endpoints of each beam element (see for example [20]). However, due to numerical instabilities in solving the finite dimensional approximations to (5) and (6) with the 4 degree of freedom scheme, an approximation using 2 degrees of freedom, displacements at the end of each beam element, was developed. Numerical results from this approximation scheme are presented in this paper.

For this discretization and set of parameter values, it was found that the largest possible H_∞ controller parameter θ that will guarantee $(I - \theta^2 P\Pi)$ being positive definite is 0.38. Therefore, all H_∞ controllers implemented in this paper use $\theta = 0.38$. Still, the reader is reminded of the interest in examining the sensitivity of the state with respect to θ variation. In this work, the lift function is neglected, but it is included in the written statement of the model and relevant weak formulations since, ultimately, it is the intent that the BMB system will closely model a MAAS system.

Approximate state and state sensitivities to θ are computed for several values of the parameter, namely $\theta = 0.00$ (LQG compensator), $\theta = 0.10$, $\theta = 0.20$, and $\theta = 0.38$. For reference, the uncontrolled state plot is given in Figure 2. It is the intent to design a feedback controller that will stabilize the unstable uncontrolled system. The primary question of interest in this paper is how to take advantage of the aeroelastic wing feature of a MAAS to aid in control design efforts. A secondary goal is to examine how sensitive the controlled beam displacements are to variation in the H_∞ control parameter, θ. Figure 3 contains plots of the state sensitivities to the θ parameter. As can be seen from these simulations, the state sensitivities for the various θ values depicted are
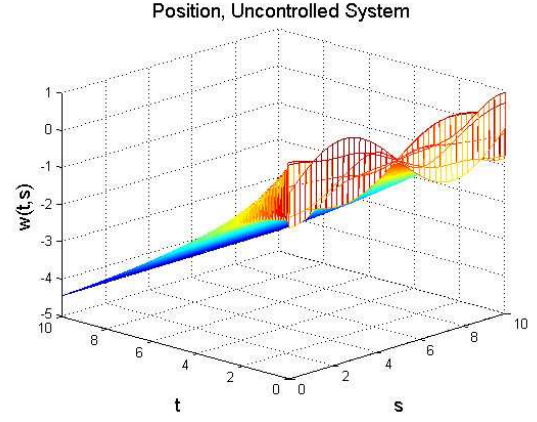
virtually indistinguishable. This observation suggests that for the BMB system with the chosen parameters, the actual θ value used in control design may not be critical in regard to controlled state performance.
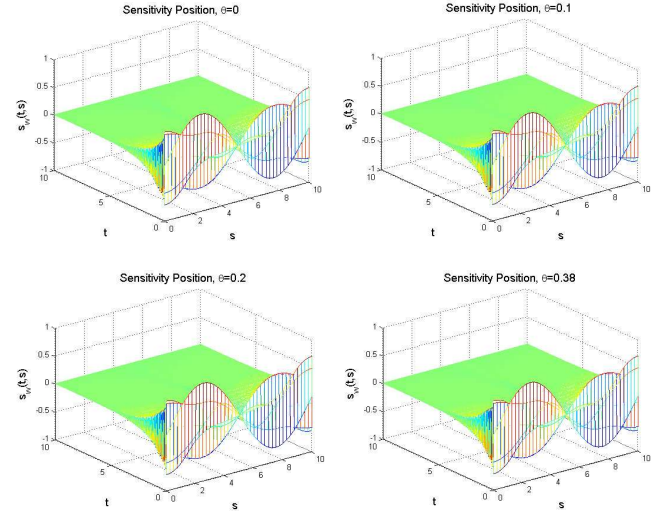

Fig. 3.   State Sensitivities: $\theta = 0.00$ (top left), $\theta = 0.10$ (top right), $\theta = 0.20$ (bottom left), $\theta = 0.38$ (bottom right)

Additionally, the authors examine $s_u(t; \theta)$, the sensitivity of the controller with respect to θ, and these plots are found in Figure 4. The results demonstrate that the controller becomes more sensitive to θ as this parameter is increased. Since the value of θ is closely connected to the robustness of the controller, this observation suggests that the more robust the controller, the more sensitive it is to θ.

As a means to gain insight into the problem of sensor placement, the authors examine the control and observer functional gains, contained in Figures 5 and 6, respectively. An area where a functional gain is large indicates that one should consider placing a sensor in that region of the spatial domain since it appears to contribute significantly to the control design. Due to the small scale of the control bending gains in Figure 5, there is no useful information to ascertain
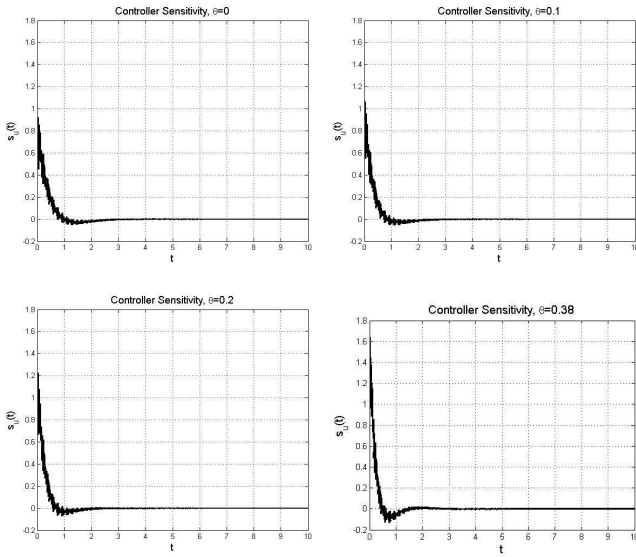
Fig. 4. Controller Sensitivities: $\theta = 0.00$ (top left), $\theta = 0.10$ (top right), $\theta = 0.20$ (bottom left), $\theta = 0.38$ (bottom right)

from this plot. The control velocity gains suggest that sensors be placed at the free ends of the beams. The observer gains in Figure 6 are nearly constant so that there is no useful information to ascertain from this plot. It should be noted that there may be a problem with convergence of the functional gains, as can be seen from the plots. Normally, one examines the functional gains for various discretizations with increasing N to verify that gain convergence has been achieved. However, for $N = 5$ and $N = 10$ for each beam, MATLAB® reported that the Grammian matrix $W = [K_0\ 0; 0\ M_0]$ was nearly singular so that computation of W^{-1}, as required for gain computation (see [13]), may not be accurate. For this reason, and the fact that finer discretizations than $N = 40$ on each beam are computationally intractable due to the cubic spline basis required for Euler-Bernoulli beam approximations, only gain computations for $N = 20$ and $N = 40$ for each beam are shown.
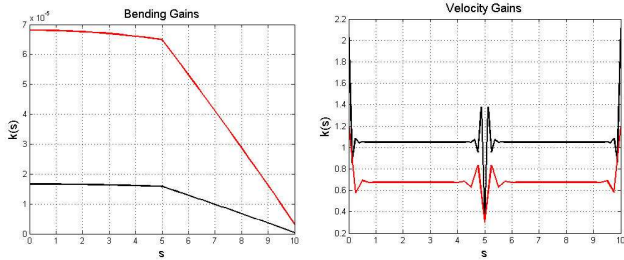

Fig. 5. Control Functional Gains for $\theta = 0.38$ with $N = 20$ (red) and $N = 40$ (black) for each beam: bending gains (left) and velocity gains (right)

V. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In the paper, the BMB system (11), (12) is approximated by Hermite interpolating cubic splines with 2 displacement
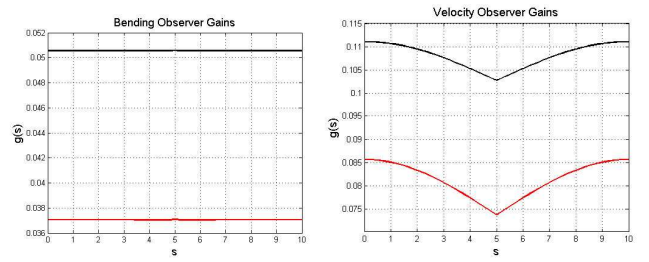

Fig. 6. Observer Functional Gains for $\theta = 0.38$ with $N = 20$ (red) and $N = 40$ (black) for each beam: bending gains (left) and velocity gains (right)

degrees of freedom for each beam element. Approximate state and state sensitivities to θ are computed for several values of the parameter θ. It is observed that the state sensitivities for the various θ values depicted are virtually indistinguishable. This suggests that for the BMB system with the chosen parameters, the actual θ value used in control design may not be critical in regard to controlled state performance. The authors also examine the sensitivity of the controller with respect to θ, and these results suggest that the more robust the controller, the more sensitive it is to θ. As a means to gain insight into the problem of sensor placement, the authors examine the control and observer functional gains. The results suggest that placing sensors near the endpoints of the free ends of the beams may prove advantageous to control design.

B. Future Works

Numerical instabilities in solving the finite dimensional approximations to the algebraic Riccati equations were discovered, and this needs to be investigated. More investigation needs to be done on the sensor placement problem in order to take into account sensor placement effects on performance and robustness. Instead of considering a point load between the two beams, the authors are interested in including in the BMB model a mass of some nonzero size. The authors plan to include a realistic aerodynamic force for the lift function.

VI. ACKNOWLEDGMENTS

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Attitude Control Augmentation Using Wing Load Sensing - A Biologically Motivated Strategy

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Many flying animals are able to achieve highly robust flight without feedback from dedicated angular rate sensors. In general, these animals use their vision systems to provide attitude rate and orientation information. Limitations of vision based measurements for stabilizing the body include the high level of latency incurred in the visual processing system and the need to maintain some level of ocular isolation in order to achieve adequate image quality. This paper investigates the potential for load sensors on the aerodynamic surfaces to enhance body platform stability. Two complementary techniques are explored: one using body torque error to control actuator position and the other using body force sensing to compensate for high optical feedback latency. The benefits of responding reflexively to forces on the aerodynamic surfaces include low latency, a reference frame inherently consistent with the control actuation, and alleviation of the necessity for control based explicitly on aerodynamic characterization. This paper uses 6DOF simulation to demonstrate the robustness derived from load sensing in a turbulent flow field with high levels of plant uncertainty and optical feedback latency. The results of this paper suggest that direct sensing of forces acting on the body can significantly enhance the robustness and performance of an attitude control system, perhaps giving insight into how natural systems can fly with high levels of damage, coarse sensors, and large sensorimotor information processing latencies.

Nomenclature

ψ	Azimuth or Yaw Euler Angle	ω_n	Natural Frequency
θ	Elevation or Pitch Euler Angle	J	Moment of Inertia
ϕ	Bank or Roll Euler Angle	ζ	Damping Ratio
V	Inertial Velocity Magnitude	K_p, K_d	Proportional and Derivative Control Gains
$[p, q, r]$	Body Angular Rate Components	K_t	Gain Associated with Torque Feedback
b	Reference Lateral Length	Δt_{opt}	Optical Feedback Latency
c	Reference Longitudinal Length	$\theta_m, \dot{\theta}_m, T_m$	Measured Angle and Torque States
LQR	Linear Quadratic Regulator	PD	Proportional Derivative Control
MAV	Micro Air Vehicle	PID	Proportional Integral Derivative Control
$6DOF$	Six Degree of Freedom Simulation	PDT	Proportional Derivative Torque Control
$GenMAV$	Generic Micro Air Vehicle		

I.   Introduction

Insects are commonly used as research subjects for flight control physiology studies due to the reduced complexity of their morphology, physiology, and behavioral response. The ability of insects to perform precision navigation is also widely studied.[1][2] Flying insects are abundant and readily available, and they are considered models for the characteristics desired in man-made micro-air vehicles.[3][4] Insects robustly deal with damage to their bodies and uncertainty in their environments. They are adaptable, autonomous, and can readily change behavioral objectives. Insects, in all of their various forms, have a wide array of discrimination and target-tracking capabilities, using optical, acoustic and chemo-receptive modalities.[5][6][7] All flying insects appear to take advantage of optical rate feedback in their flight control systems. Insects of the order Diptera, flies, also use mechanoreceptive angular rate feedback from the halteres.[8][9][10] Those insects having only optical rate feedback are capable of remarkable flight performance. Given the amount of latency inherent in the optical feedback pathways, the specific mechanisms through which flight stability is

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achieved remain unclear.[11] It is this characteristic that is the motivation for the work described in this paper.

The intent of this research is to understand the benefits of load sensing on aerodynamic surfaces for attitude stabilization. The bodies of animals are sensor rich. Strain sensors that respond to internal and external forces on the exoskeleton are common if not universal.[12][13] In addition to having influence on high-level behaviors, these sensors have evolved to provide low-latency reflexive response as well. The wings of insects have cuticular strain sensors, referred to as campaniform sensilla, distributed along the structural veins, as well as chordotonal organs that stretch and respond to motion of the wing hinge.[14] These sensors encode magnitude of the wing load through species-dependent mechanisms.[15] The pathways to the wing control muscles are short, with low latency, leading to speculation that they are directly involved in flight control.[16] Given the relatively high level of latency involved in rate feedback from the insect visual system, it is likely that the wing load sensors play a direct role in attitude stabilization. This role is especially indicated in natural systems that do not have a direct, low-latency means of measuring angular rate attached to the main body, i.e., halteres or other gyroscopic organs.

The point of departure for this activity was a subsequently discarded hypothesis: strain sensed on the wings is proportional to angular rate in the body frame. Therefore, by reacting to wing strain, a winged vehicle could apply a dissipative damping force that ensures attitude stability. The origin of this thought process was the understanding that a steady state roll motion would induce a differential angle of attack on the wings proportional to roll rate. This differential angle of attack would in turn result in a differential force, or roll damping, on the wings which might be sensed and controlled. Therefore, the differential wing load would be proportional to roll rate. While the described rate damping effects are very real, the inability to separate other dynamic causal effects, e.g., control surface deflection and transient gusts, from the steady state mechanism hypothesized was felt to be insurmountable. Alternative mechanisms were therefore pursued.
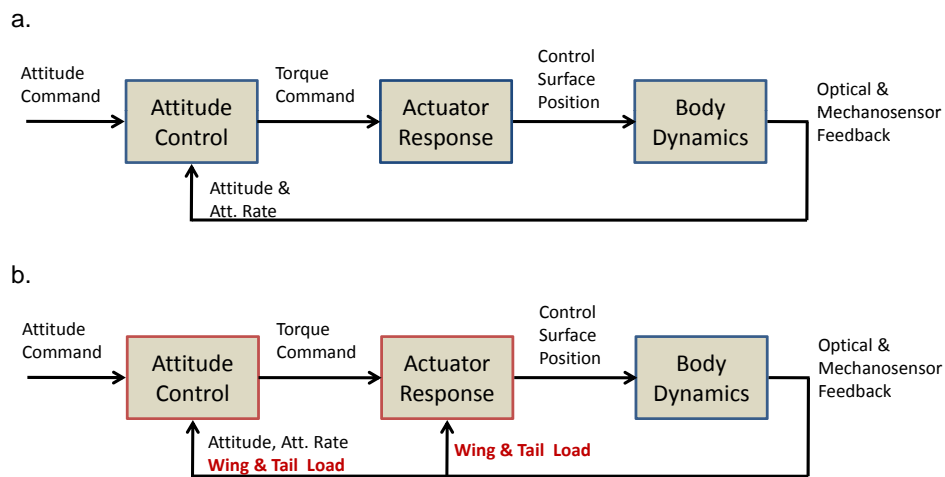
Figure 1. a) Baseline attitude control without load feedback. Actuators assumed have a first order open-loop response. b) Attitude with load feedback to optimize responsiveness of the attitude controller and to reject disturbances and errors in actuated body torque. The closed-loop actuator response is modeled as a damped second order system.

In its simplest form, the attitude control of a flight vehicle can be described as in Figure 1a. Angular rate and orientation resulting from the system dynamics are sensed, and the measurements are fed back into the attitude control system. The attitude control system then commands a control surface response, intended to produce a torque on the body in order to reduce attitude state errors. There are two fundamentally distinct ways in which strain measurements might influence the attitude control design: through regulation of the actuation commands sent to the control surfaces and through augmentation of the attitude controller, Figure 1b. In the first way, the measured error in the body torque achieved by the vehicle control surfaces can be driven to zero using the actuators. The source of this error might be uncertainty in the plant characteristics or a torque disturbance on the body from external sources such as turbulence. The second way that load sensing might be used in the control system, direct use in the attitude control formulation, has multiple possibilities as well. Attitude control systems normally include proportional and integral control on sensed attitude, with damping and robustness provided through rate feedback. A disturbance force acting on the body must produce body angular rate before the controller moves the control effectors to cancel it. If some direct measure of angular acceleration could be sensed, the attitude controller could potentially obtain a more optimal tracking response. In addition, if torque was estimated from the strains sensed, with knowledge of the inertia, a low latency measure of

angular acceleration could be obtained. With this estimate, high-latency optical angular rate feedback, or phase error, might be directly mitigated to a first order.

II.   Model and Simulation Description

Figure 2. Attitude control demonstrations were based on a model of the AFRL GenMAV vehicle. Aerodynamic coefficients were calculated using AVL. Models assumed a configuration with ailerons, not shown in the hardware depicted.

The specific mechanisms by which load sensing is used in natural systems for flight stabilization are not known. To demonstrate potential applications and the associated benefits, a model of the Air Force Research Laboratory (AFRL) developed Generic Micro-Air-Vehicle (GenMAV) was employed, as shown in Figure 2. This choice avoided the complexity of modeling a flapping wing system, allowing for more straightforward conceptualization of engineering applications, while still providing direct insight into potential biological mechanisms.

GenMAV is a conventionally-shaped air vehicle with a high-wing configuration, a wingspan of 24" and a chord of 5". It has a conventional tail with a horizontal surface of 12" and a vertical surface of 4.6". The fuselage is 16.5" in length and approximately 3" in diameter at its widest point. GenMAV is a bank-to-turn vehicle controlled by a pair of elevons that make up 50% of the chord on the horizontal stabilizer. Its body and wings are comprised of carbon fiber with enough layers to ensure adequate rigidity. For this investigation, the GenMAV is modeled with conventional ailerons, elevator, and rudder, a different control configuration from the actual hardware design. GenMAV was developed as a reference vehicle for research conducted within and outside of AFRL.[17] The generic design is based on several iterations of MAVs previously studied in AFRL and provides a convenient baseline from which various MAV technologies can be explored.[18]

Control system modeling of the flight vehicle was accomplished in the Matlab Simulink[TM] environment. The 6DOF simulation environment was constructed using a direct implementation of the quaternion dynamics model documented by Phillips.[19][20] To provide aerodynamic disturbances, the continuous Dryden turbulence model within the Aerospace Blockset was used, with the wind speed parameter set to approximately 10 percent of the MAV ground speed. Characterization of the GenMAV vehicle, in order to provide an aerodynamic truth model, was accomplished with the Athena Vortex Lattice (AVL) code. AVL was developed by Harold Youngren of MIT, and subsequently by Mark Drela (also of MIT) to provide aerodynamic and flight-dynamic analysis of rigid aircraft with arbitrary configurations.[21] The program applies thin airfoil theory to predict the inviscid aerodynamic forces and moments acting on the lifting surface of an air vehicle. Thin airfoil theory approximates the airfoil as a combination of uniform flow and a vortex sheet placed along the camber line. This leads to the aerodynamic force and moment being primarily a function of angle of attack and camber line geometry. Based on the assumptions behind thin airfoil theory, AVL is best suited for applications involving thin lifting surfaces, i.e., maximum thickness of 12% chord or less, at small angles of attack and sideslip. In AVL, the lifting surfaces of an aircraft are modeled as single-layer vortex sheets discretized into horseshoe vortex filaments. Flow is assumed to be quasi-steady and within the limit pertaining to small reduced frequency. This

translates into the following limits for each of the dimensionless flow rate parameters:

$$-0.10 < \frac{pb}{2V} < 0.10$$

$$-0.03 < \frac{qc}{2V} < 0.03$$

$$-0.25 < \frac{rb}{2V} < 0.25.$$

Given that thin airfoil theory deals with 2-D potential flow, drag due to viscous effects is not calculated in AVL, and the lift coefficient is a linear function of angle of attack. Overall drag is represented as a combination of lift-induced drag plus an approximation for parasitic effects. In addition to static coefficients, AVL provides damping coefficients, including the coupled terms between roll and yaw, and control surface derivatives. The full complement of aerodynamic coefficients was used for this work.

For demonstration of the benefits of torque feedback, the attitude control was implemented using three independent PD controllers; body rate and attitude error were assumed to be optically observable. Pitch angle was used directly to control altitude error. The outer altitude control loop was in the form of PID control, allowing the integral term to account for gravity bias. The attitude loops were tuned to respond as critically damped second order systems with nominally a 5 Hz natural frequency. Attitude control output was in the form of a torque command for each body axis; i.e.,

$$Commanded\,Torque = J\ddot{\theta}$$
$$= -J\omega_n^2(\theta_m - \theta_{com}) - J2\zeta\omega_n\dot{\theta}_m \qquad (1)$$
$$= -K_p(\theta_m - \theta_{com}) - K_d\dot{\theta}_m,$$

where K_p and K_d are the proportional and derivative control gains, θ is an angular degree of freedom with an associated inertia J. The desired damping ratio and natural frequency are represented by ζ and ω_n, respectively.
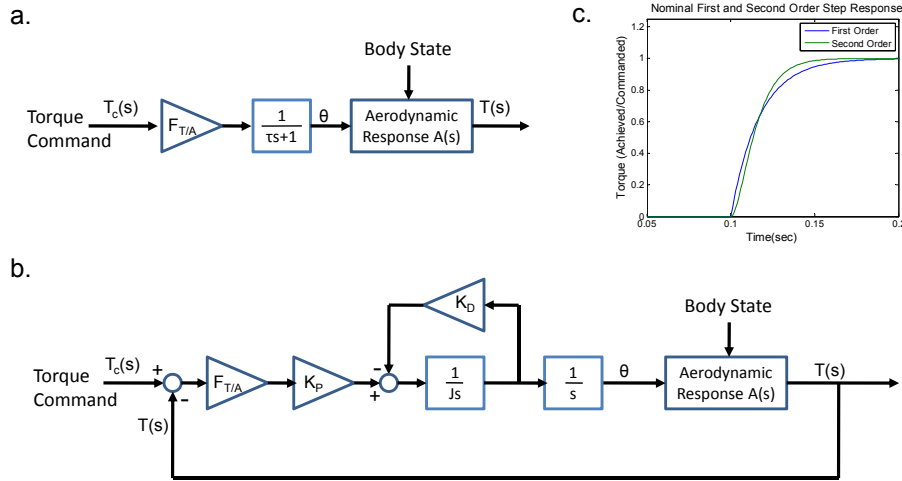
Figure 3. Actuator response models used for load feedback 6DOF demonstrations: a) first order response model, b) second order torque error regulator. The nominal response time constants for both models were defined to be 17 ms as shown in c). In a) and b), θ represents the achieved control surface deflection and $F_{T/A}$ represents a nominal scale factor to convert torque to control surface deflection angle.

A nominal first order control surface actuator response model was used for baseline comparison. Alternatively, closed-loop actuators, which used measured body torque error to drive the ailerons, elevator, and rudder, were modeled as second order damped torque motors with angular limits at +/- 30 degrees. The natural frequency of the second order actuator control loop was nominally 20 Hz, having a 17 ms time constant for 63% response. The first order actuator was also defined with a 17 ms time constant for consistency. Both actuator response models used a common scale factor, $F_{T/A}$, derived around straight and level flight conditions to convert torque to angle, Figure 3. Under nominal conditions, to the degree that the second and first order responses were similar, the airframe response would be expected to be similar. Under conditions of degraded control realization and non-zero latency, significant differences

would be expected due to the inability of the controller without torque feedback actuation to reflexively respond to errors and disturbances.

To demonstrate the potential benefit from augmenting the attitude controller with wing load feedback, a formulation was derived to use the assumed low-latency measurement of body torque to compensate for the destabilizing influence of high latency in the optical feedback pathway. To derive the control expression used, both inertia and feedback latency are assumed to be known to some approximation. The control gains associated with measured angle, θ_m, angular rate, $\dot{\theta}_m$, and torque, T_m, are required:

$$Commanded\ Torque = -\bar{K}_p(\theta_m - \theta_{com}) - \bar{K}_d\dot{\theta}_m, -\bar{K}_tT_m.$$

These new gains are found in terms of the gains in (1), the latency, Δt_{opt}, and the inertia, J, using simple Taylor series approximations:

$$\dot{\theta}_{est} = \dot{\theta}_m + \frac{T_m}{J}\Delta t_{opt} \tag{2}$$

$$\theta_{est} = \theta_m + (\dot{\theta}_m + \frac{T_m}{J}\Delta t_{opt})\Delta t_{opt} + \frac{T_m}{2J}\Delta t_{opt}^2$$

$$= \theta_m + \dot{\theta}_m\Delta t_{opt} + \frac{3T_m}{2J}\Delta t_{opt}^2. \tag{3}$$

Substituting the estimates represented by (2) and (3) for the measured quantities in (1), then collecting terms, provides the following expressions for the new gains:

$$\bar{K}_p = K_p \tag{4}$$

$$\bar{K}_d = (K_p\Delta t_{opt} + K_d) \tag{5}$$

$$\bar{K}_t = \left(K_p\frac{3\Delta t_{opt}^2}{2J} + K_d\frac{\Delta t_{opt}}{J}\right). \tag{6}$$

Efforts to develop an optimal attitude control law using body force states to minimize a cost function, as in LQR, were not complete at the time of this publication.

III.   Results

Two test cases were devised to demonstrate the benefit of load sensing on dynamic performance. Both test cases included the turbulence model previously described and an initial one meter step command in altitude. The first test case demonstrated performance with and without degraded control response. To model the degraded control response, the angular response of all control surfaces was cut in half, thereby modeling a 50% degradation in control surface effectiveness. Linear forces through the center of gravity were not degraded.

Figures 4a and 4b show the roll and yaw attitude in the presence of turbulence and a one meter altitude step command with no torque feedback. The two time histories represent cases with and without control system degradation. Figures 4c and 4d show the same two cases with torque feedback to control actuator position. The cases with torque feedback to the actuator show roughly an order of magnitude better disturbance rejection. Both with and without torque feedback, an increase in attitude response is seen as a result of the control surface degradation. Figure 5 demonstrates the increased response of the rudder and aileron in the presence of control degradation without torque feedback, a) and b), and with torque feedback, c) and d). The control surface positions are similar in character with increased amplitude for the torque feedback control. As demonstrated by Figure 4, the closed-loop actuator more effectively dealt with the deviations from the commanded body torques.

The second test case involves introduction of latency into the state feedback that drives the attitude control law. In animal systems, in particular those that do not have highly dedicated rate sensing physiology, optical flow provides a primary means for sensing angular motion. In insects, the neuronal processing of vision motion may introduce 30 ms or more latency into the feedback process, depending on species and ambient light level. This delay would be expected to have a detrimental impact on the attitude control system. The strain mechanosensors typically have a much more direct pathway to the muscles that they stimulate. Campaniform sensilla, the load sensors on insects, can induce a response in the muscles in an order of magnitude less time than that achieved by the vision system. The haltere to motor neuron pathway in dipertan insects is a well characterized example of this type of quick reflexive response. For this test case, a latency of 3 ms on the torque feedback and 10 ms on the optical feedback was sufficient to demonstrate the benefit of closed-loop torque regulation.
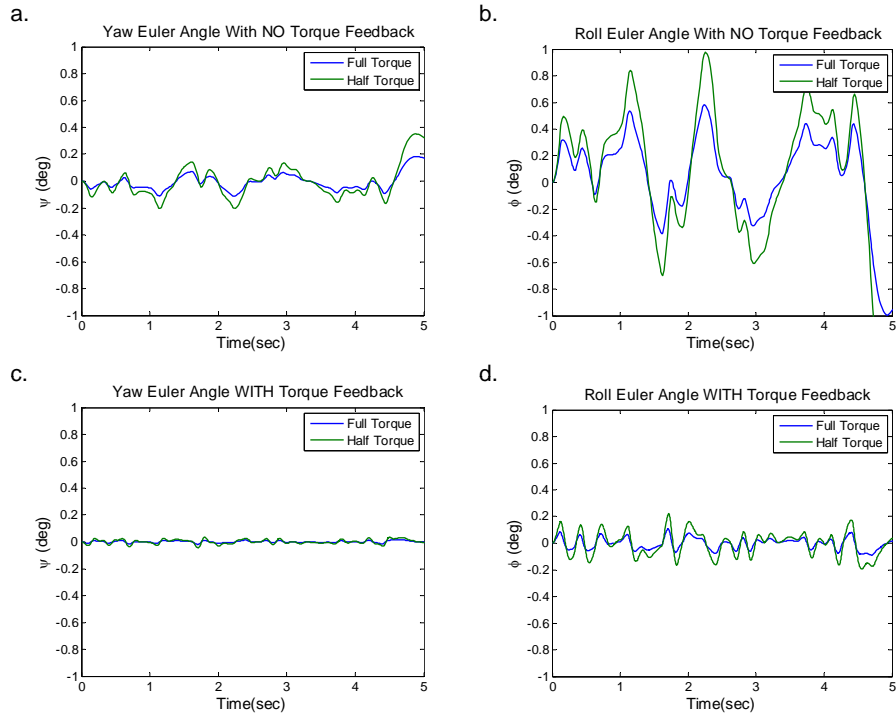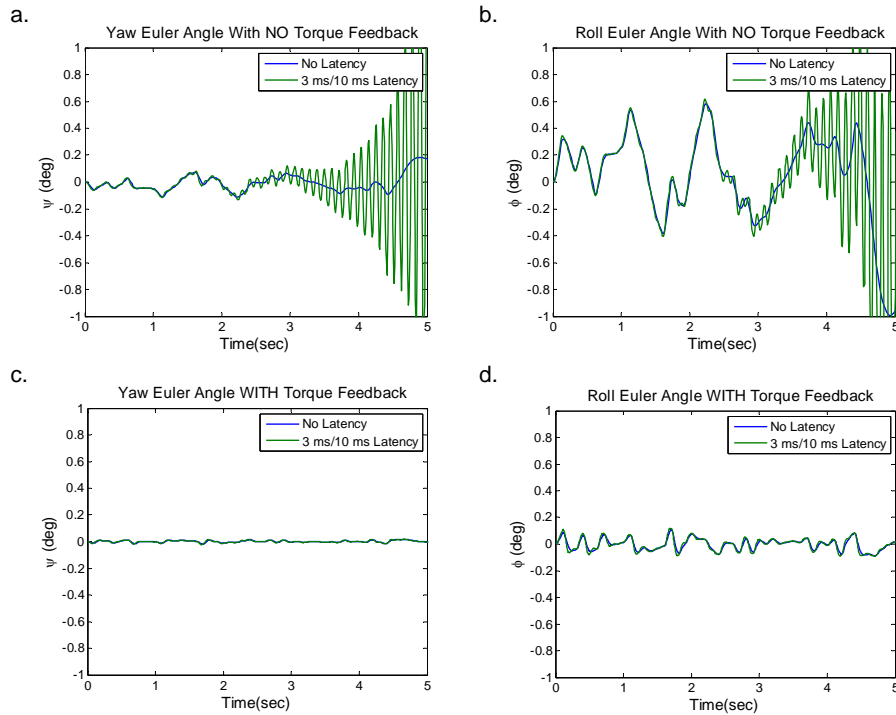
Figure 4. Euler angle response of GenMAV without and with torque feedback to actuators for the case of 50% degradation in control capability. a) Yaw Euler angle with open-loop rudder control. b) Roll Euler angle with open-loop aileron control. c) Yaw Euler angle with torque feedback to rudder control. d) Roll Euler angle with torque feedback to aileron control.
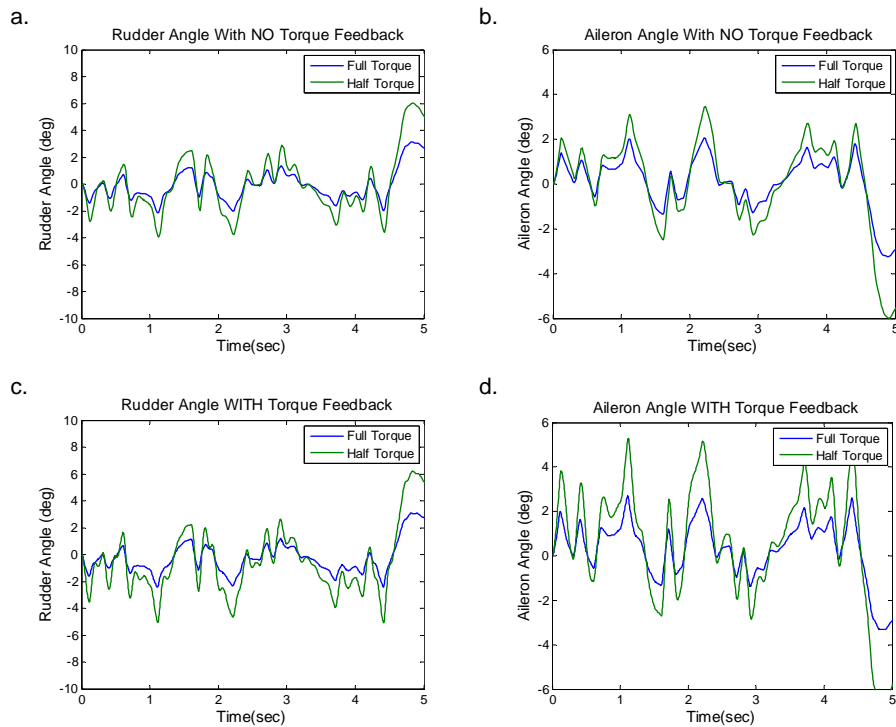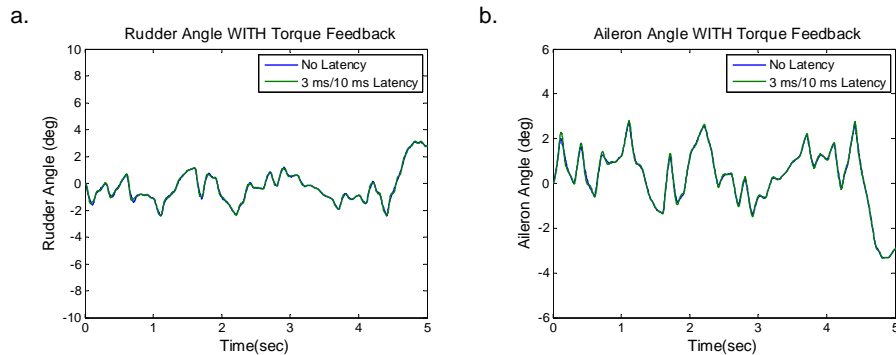

Figure 5. Rudder and aileron control surface response for the case of 50% degradation in control capability (Figure 3). a) Open-loop rudder response and b) open-loop aileron response. c) and d) show response of the rudder and aileron with closed-loop actuator control.

Figures 6a and 6b demonstrate that, without torque feedback, a highly oscillatory yaw and roll attitude response results in the presence of 10 ms of latency. This response is stimulated by turbulent disturbances. Note that the bandwidths of the attitude loops were tuned for the ideal zero latency case. In contrast, Figures 6c and 6d show the same comparison with the torque feedback to the actuators. Figure 7 shows the corresponding control surface angles for the two cases from Figures 6c and 6d. The two curves in this figure depict a very similar response. The fact that actuator response does not change significantly in the presence of the optical feedback latency indicates that the torque feedback loop is primarily responsible for mitigating the effect of the turbulence induced torque disturbances. The improved disturbance rejection delays the onset of system oscillation as latency increases.

a.

Yaw Euler Angle With NO Torque Feedback

b.

Roll Euler Angle With NO Torque Feedback

c.

Yaw Euler Angle WITH Torque Feedback

d.

Roll Euler Angle WITH Torque Feedback

Figure 6. Euler angle response of GenMAV without and with torque feedback to the actuators for the case of 3 ms torque feedback latency and 10 ms attitude state feedback latency. a) Yaw Euler angle with open-loop rudder control. b) Roll Euler angle with open-loop aileron control. c) Yaw Euler angle with torque feedback to rudder control. d) Roll Euler angle with torque feedback to aileron control.

a.

Rudder Angle WITH Torque Feedback

b.

Aileron Angle WITH Torque Feedback

Figure 7. Rudder and aileron control surface response for the case of 3 ms torque feedback latency and 10 ms attitude state feedback latency (Figures 6c and 6d). a) Open-loop control and b) torque regulated control.

As latency increases further, even with torque feedback to the actuator, the system begins to destabilize as shown in Figure 8a. In this example, 30 ms of latency was simulated. Figure 8b shows the response with the PD attitude controller augmented with torque to compensate for the latency (PDT control), reference equations (4)-(6). In this case, the system responds with some pitch oscillation in response to the one meter step in altitude, but quickly stabilizes,

closely matching the zero latency baseline case. Note that the motion that dominates in all cases described is pitch motion. There is no mechanism in the defined control scheme to respond to measured z-force error except through pitch control. The resulting motion to affect a decrease in altitude error is much larger than the residual motion in yaw and roll. In a flapping wing design, where z-force could be controlled independently, this coupling of degrees of freedom would not necessarily be required.
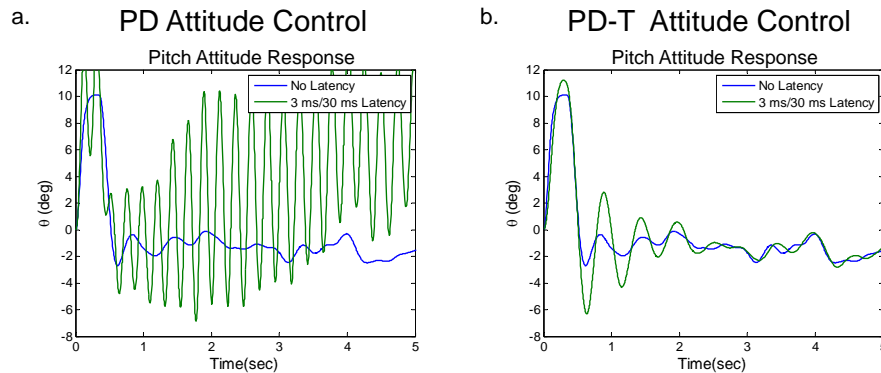
Figure 8. Pitch response for the case of 30 ms optical latency and closed-loop actuator control. Figure a) shows the highly oscillatory nature of the response without latency compensation. Figure b) shows the improved response with torque augmented attitude control to compensate for the latency.

IV.   Discussion

The results in this paper demonstrate the ability of wing load sensors to improve attitude control robustness and disturbance rejection in the presence of significant uncertainty in plant characteristics. By directly measuring the torque around a given axis, the error with respect to the torque commanded by the attitude control law can be reduced without dependence on known aerodynamic characteristics of the airframe. Through the same mechanism, torque disturbances on the airframe can be dealt with through high speed reflexive control, leaving the outer attitude control loop to deal with lower frequency optical tracking. This wing load feedback mechanism may explain the robustness of insect flight, where significant damage to wings is tolerated and high variations in control performance occur due to such factors as temperature, age, individual variation, and metabolic state.

The results shown in this paper rely on many assumptions with respect to sensor implementation. Actual implementation of strain sensors may be a significant hurdle to realization of the results shown. Nature has evolved systems that rely on large numbers of simple sensors spread throughout the body structure to sense and respond to interaction with the environment. While individual sensors may be very poor detectors of magnitude, in concert, a number of simple sensors spread throughout a structure might have a very large effective dynamic range. The human engineering approach is to build more elaborate sensors that individually achieve the required dynamic range. Inherent in these approaches is a trade-off between integration complexity and robustness to damage. If one of the many simple sensors associated with the insect wing is not functional, a small price is paid in terms of overall dynamic range, but the system still functions. If the single, more elaborate sensor on the man-made system is damaged, the result might be catastrophic. Significant engineering development in materials and manufacturing technology would be required to duplicate the design paradigm that is prevalent in natural systems. However, similar performance characteristics might be achievable by mimicking a low-latency, load-based control mechanism without duplicating the sophistication in materials and manufacturing seen in nature.

To achieve the results shown, either strain sensors would have to be placed near the body on the aero surfaces, or the angular acceleration of the body would need to be measured directly. With knowledge of the body inertia characteristics, the net torques on the body could be deduced from the angular accelerations. The feedback to the modeled closed-loop actuator is an assumed estimate of the net torque on the body. The calculations and calibrations required to realize actual quantitative estimates of torque around the center of gravity could become very elaborate. Clearly, nature is not explicitly relying on quantitative estimates of torque around the center of gravity. Natural designs take maximum advantage of symmetry and the differential effect of control force application across the plane of symmetry. In fact, strain sensors on the left half of the body may influence left wing control, while sensors on the right half influence right wing control, without a significant contralateral influence, as in the halteres of flies. The

net effect of the forces would still result in a stabilizing influence. The primary requirement is a signal, related to the net torque on the body, that can be driven to zero or to a correctly biased state, thereby driving the torque error to zero. This should be achievable with symmetric placement of strain sensors on the right and left aero surfaces. Compensation for residual biases can be realized through appropriate application of controller integral terms and the aerodynamic stability inherent in the basic design.

The fundamental idea of using feedback to eliminate uncertainty in the output of an actuator is not new. For example, hydraulic torque motors are sometimes implemented with a pressure loop around the valve to reduce the impact of hydraulic resonance. The same technique is more generally used to eliminate nonlinearities in open-loop actuator response. Treating the entire airframe as a torque motor with the error driving the control surface state is a deviation from conventional attitude control techniques. The requirement for a fail-safe feature, in case of feedback interruption, must be taken into consideration; lacking a feedback signal, the control surfaces will be driven to the limits in an attempt to reduce the error.

The techniques described in this paper might allow for MAV designs that come closer to the performance and robustness of natural systems. An additional objective of this research is decreased cost and complexity of MAV designs. Obtaining this goal is dependent upon replacement of more costly or complex rate sensors. This described control technique relies on the ability to implement the strain or load sensing transducers and the ability to obtain the requisite outer loop rate and tracking estimates from multi-use optical sensors. This objective configuration mimics many insect sensor architectures. Nature is clearly able to achieve remarkable agility, behavioral complexity, and robustness in extremely small packages through mechanisms that scientists and engineers are only beginning to understand. The human tendency to attribute undue complexity to systems that we do not understand should be considered. A concept as simple as reflexive response to wing load sensing could potentially explain much about the robustness and performance capability seen in natural flying systems.

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